Oil Compressibility Correlations

by

Abdulrahman Saleh Ali Al-Jarri

A Thesis Presented to the

FACULTY OF THE COLLEGE OF GRADUATE STUDIES

KING FAHD UNIVERSITY OF PETROLEUM & MINERALS

DHAHRAN, SAUDI ARABIA

In Partial Fulfillment of the
Requirements for the Degree of

MASTER OF SCIENCE

In

PETROLEUM ENGINEERING

June, 1990

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This thesis, written by Mr. Abdul-Rahman Saleh Al-Jarri under the direction of his Thesis Advisor and approved by his Thesis Committee, has been presented to and accepted by the Dean of the College of Graduate Studies, in partial fulfillment of the requirements for the degree of MASTER OF SCIENCE in Petroleum Engineering.

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DEDICATION

To my Parents and Wife

ACKNOWLEDGEMENT

Praise and gratitude be to the Almighty, the creator and sustainer of the Universe, and peace be upon his Prophet Muhammad.

My sincere appreciation and gratitude to Dr. Muhammad Al-Marhoun who, as my Thesis Committee Chairman, guided and helped me throughout my research. I would also like to express my sincere gratitude to Dr. Hasan Y. Al-Yousef and Dr. Habib Menouar for their valuable suggestions and instructions. I would like to thank Mrs. N.A. Al-Mousli, Mr. M. Chichakli, Mr. J. Rouser, Mr. H. Bayona, Mr. D. Zeunert and Mr. M. Hashem from Saudi Aramco for their support and encouragement. I am also grateful to Saudi Aramco for permission to use the data. Finally, I would like to thank my wife for her patience, understanding and encouragement which made this work possible.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Page #

NOMENCLATURE

A = sum of mole fractions of CO_2 and H_2S

$\vec{a}$ = $(n+1)$ vector

$\hat{a}$ = least-squares solution

a_0 = intercept

$a_i's$ = regression coefficients

B_o = oil formation volume factor, RB/STB

B_g = gas formation volume factor, RB/SCF

B = mole fraction of H_2S

C_o = oil isothermal compressibility

C_{ob} = oil isothermal compressibility at and below bubblepoint pressure, psi^{-1}

E_a = average absolute percent relative error

E_i = relative deviation, %

E_{max} = maximum absolute percent relative error

E_{min} = minimum absolute percent relative error

E_r = average percent relative error

n = total number of components in the gaseous state

n = total number of independent variables

n_d = number of points

P = pressure, psia

P_b = bubblepoint pressure, psia

P_{ci} = critical pressure of component i, psia

P_{pc} = gas pseudo-critical pressure, psia

P_{Tc} = adjusted pseudo-critical temperature °R

r = correlation coefficient

R_{sb} = solution gas-oil ratio at P_b conditions, SCF/STB

R_s = solution gas-oil ratio, SCF/STB

s = standard deviation, %

T = reservoir temperature, °R

T_{ci} = critical temperature of component i

T_{pc} = gas pseudo-critical temperature

V = oil volume, bbls

X = $n_d \times (n+1)$ matrix

x_e = estimated values

x_i = independent variable

x_m = measured values

$\bar{x}$ = average value

y = dependent variable

y_i = mole fraction of component i in the gaseous state

$\vec{y}$ = n_d vector

Z = real gas deviation factor

ε_3 = adjustment factor

γ_g = gas relative density, air = 1.0

γ_o = oil relative density, water = 1.0

خلاصة الرسالة

اسم الطالب الكامـــل : عبدالرحمن صالح علي الجري
عنوان البحـــــــث : علاقات تجريبية لإنضغاطية الزيت .
مجـــــال التخصص : هندسة بترول .
تاريخ الدرجة العلمية : يونيو ١٩٩٠م .

أمكن من هذا البحث من إيجاد صيغ تجريبية لحساب خواص الغاز الشبه حرجة (الضغط والحرارة) وإنضغاطية الزيت عند ضغط يساوي أو أقل من ضغط التشبع في الأحوال التي تكون درجة الحرارة ثابتة . إن هذه الصيغ التجريبية بالنسبة للضغط والحرارة الشبه حرجه للغاز قد أستنتجت بدلالة كثافة الغاز النسبية من ١٤٥ مجموعة من تحاليل الغاز من الشرق الأوسط . أما بالنسبة للصيغة الجديدة لإنضغاطية الزيت فقد طورت من ٢٦٣٥ نقطة من أصل ٣٧٢ إختبار للإطلاق التفاضلي للغاز من حقول الزيت في الشرق الأوسط وشمال أمريكا . إن هذه العلاقة قد أستنتجت بدلالة الضغط وضغط التشبع وكثافة الغاز النسبية ونسبة الغاز الذائب في الزيت عند نقطة التشبع والحرارة . إن المعلومات التي أستخدمت في هذا البحث تغطي مجال واسع من الضغط وضغط التشبع ونسبة الغاز في الزيت وكثافة الغاز والزيت النسبية وحرارة المكمن وإنضغاطية الزيت .

إن المعادلة تفوق سابقاتها عند أي مدى معين من الضغط بالنسبة لمعادلات إنضغاطية الزيت . وإضافة إلى ذلك ، فإن المعادلات الجديدة لخواص الغاز الشبه حرجة أكثر دقة من سابقاتها عند أي مدى معين من كثافة الغاز النسبية .

درجة الماجستير في العلوم
جامعة الملك فهد للبترول والمعادن
الظهران - المملكة العربية السعودية
يونيو ١٩٩٠م

THESIS ABSTRACT

Full Name of Student: Abdul-Rahman Saleh Al-Jarri

Title of Study: OIL COMPRESSIBILITY CORRELATIONS

Date of Degree: June 1990

This thesis presents empirical correlations for estimating gas pseudo-critical properties (pressure and temperature) and oil isothermal compressibility values at and below bubblepoint pressures. These gas pseudo-critical pressure and temperature correlations were derived as functions of gas relative density based on 145 sets of gas analysis, collected from Middle East gases. The new oil isothermal compressibility correlation, was developed using 2635 data points from 372 gas differential liberation tests collected from the Middle East and North American oil fields. This correlation was derived as a function of pressure, bubblepoint pressure, gas relative density, solution gas-oil ratio at bubblepoint conditions and reservoir temperature. The data covered a wide range of pressure, bubblepoint pressure, solution gas-oil ratio, gas and oil relative densities, reservoir temperature and oil compressibility.

The newly developed correlation clearly out-performs the existing correlation even against selected ranges of pressure for oil compressibility correlations. Moreover, the new pseudo-critical properties correlations are more accurate than the existing correlations.

MASTER OF SCIENCE DEGREE

KING FAHD UNIVERSITY OF PETROLEUM AND MINERALS
Dhahran, Saudi Arabia

CHAPTER 1

Chapter 1

INTRODUCTION

Oil isothermal compressibility values are required, among other parameters, in all solutions of transient fluid-flow problem [1]. Proper evaluation of this parameter will be useful for the interpretation of well test analysis and other reservoir performance calculations such as reserves estimates using material balance, rate performance using static reservoir pressures, effectiveness of well completion and well stimulation.

The coefficient of oil isothermal compressibility is defined as the fractional reduction in oil volume that results from a pressure increase of one psi at a particular temperature:

$$Co = -\frac{1}{V}\left(\frac{\partial V}{\partial P}\right) \qquad (1.1)$$

For saturated system with pressure at and below the bubblepoint, the volume occupied by the gas evolved from the oil during the differential change in pressure must be taken into account in the calculation of oil compressibility by considering the change in solubility

of gas in the oil compressibility equation (1.1). Oil compressibility can be evaluated from an equation developed by Perrine [2] and extended by Martin [3] when differential liberation data of reservoir fluids are available:

$$Co = -\frac{1}{B_o}\left[\frac{\partial B_o}{\partial P}\right]_T + \frac{B_g}{B_o}\left[\frac{\partial R_s}{\partial P}\right]_T \qquad (1.2)$$

However, this data is not available for all wells and oil compressibility must be calculated.

The existing oil compressibility correlation [5] is not accurate at pressures below 500 psia or bubblepoint pressures below 763 psia. The oil isothermal compressibility values, at pressure below 500 psia, are much larger and thus the existing correlation will only yield approximate results.

Moreover, in the estimation of oil compressibility values at and below bubblepoint pressure with Eq. (1.2), the gas pseudo-critical properties (pressure and temperature) must be determined in order to compute the real gas deviation factor (Z-factor) which is used in the estimation of the gas formation volume factor (B_g).

Therefore, the objectives of this thesis are to:

(1) Develop an empirical correlation to calculate the oil isothermal compressibility values at and below bubblepoint pressures.

(2) Develop emprical correlations to compute gas pseudo-critical pressure and temperature.

(3) Compare the accuracy of the existing correlations and the new ones developed in this study.

CHAPTER 2

Chapter 2

LITERATURE REVIEW

2.1 Oil Isothermal Compressibility At and Below Bubblepoint Pressure

Perrine [2] presented an empirical extension of single phase pressure buildup methods to multiphase flow situations. He suggested that improper use of single phase buildup analysis for multiphase flow could lead to errors in the estimation of static formation pressure, permeability and well condition. A theoretical foundation for Perrine's approach was established by Martin [3]. It was found that under certain conditions of small saturation and pressure gradients, the equations for multiphase fluid-flow may be combined into an equation for effective single-phase flow. After some mathematical manipulations, Martin [3] defined the oil isothermal compressibility as follows:

$$Co = -\frac{1}{B_o}\left[\frac{\partial B_o}{\partial P}\right]_T + \frac{B_g}{B_o}\left[\frac{\partial R_s}{\partial P}\right]_T \qquad (2.1)$$

With the above equation, the oil isothermal compressibility for saturated systems can be calculated when formation volume factors of oil and gas, B_o and B_g, respectively, and the solution gas-oil ratio, R_s, (all as

functions of pressure), are known from laboratory measurements (differential gas liberation test) of reservoir fluid.

2.1.1 Ramey Approach

In 1964, Ramey [4] presented a graphical method to compute the oil isothermal compressibility at pressures below the bubblepoint. The method was based on Standing's correlations of B_o and R_s for California crude oil. It requires estimation of each parameter in Eq. (2.1). The derivatives were estimated through graphical differentiation of Standing's Figs. 1 and 3 and they were shown in Figs. 4 and 5 of Ramey paper [4]. These figures are shown in Figs. 1 through 4. Therefore, this method yields only approximate results.

2.1.2 McCain et al. Correlation

Later in 1988, McCain et al. [5] developed a correlation to calculate the coefficient of isothermal compressibility of black oils at pressures below the bubblepoint. This correlation was based on 2500 data points collected from 260 well locations worldwide. In calculating oil compressibility values with the above Eq. (2.1), the derivatives of B_o and R_s with respect to pressure were obtained by first fitting these values with curves using the cubic spline interpolation method and then differentiating to obtain the derivatives at any point. The boundary

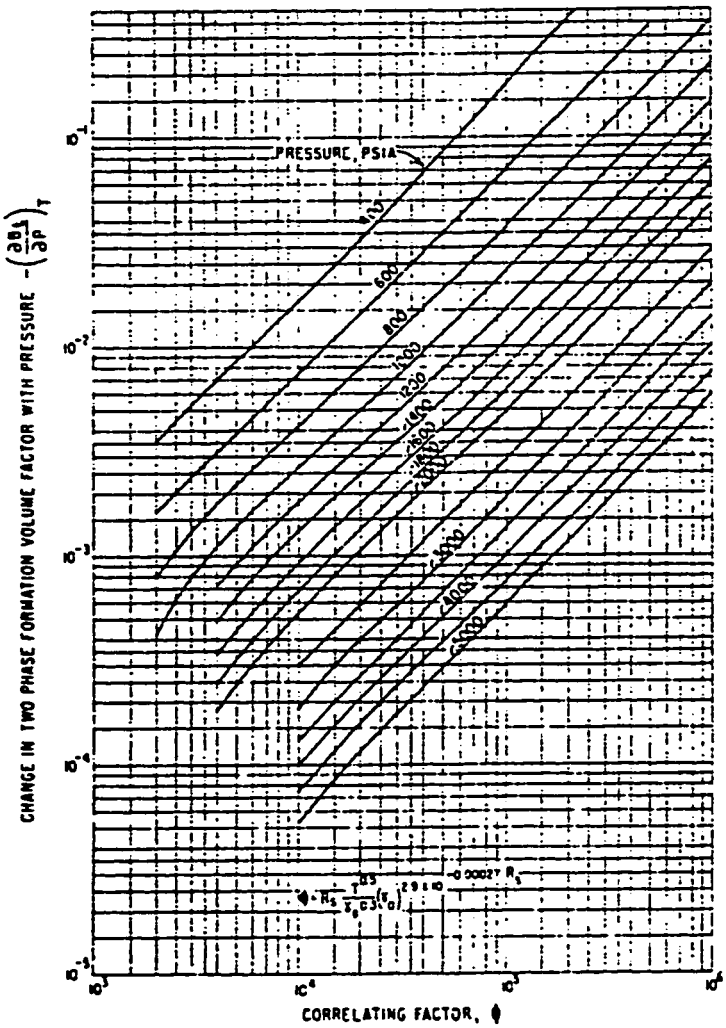


Fig.1- Change of Standing's Two-Phase Formation Volume Factors with Pressure. [4]

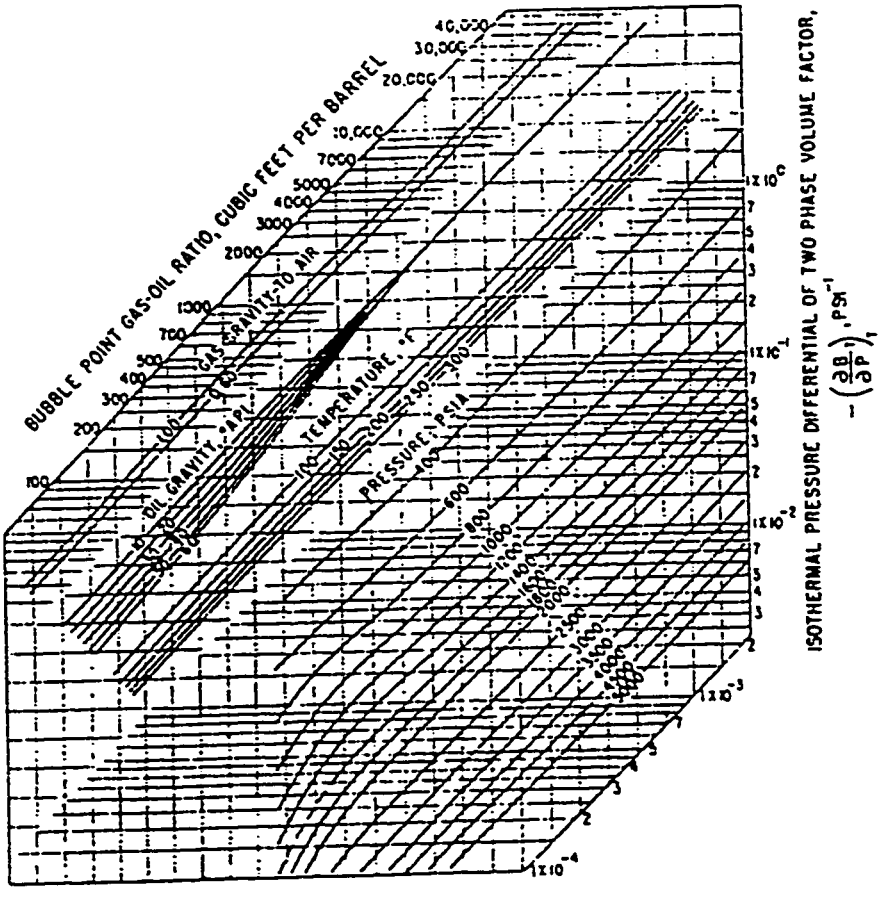


Fig.2-Isothermal Pressure Differential of Two-Phase Volume Factor. [4]

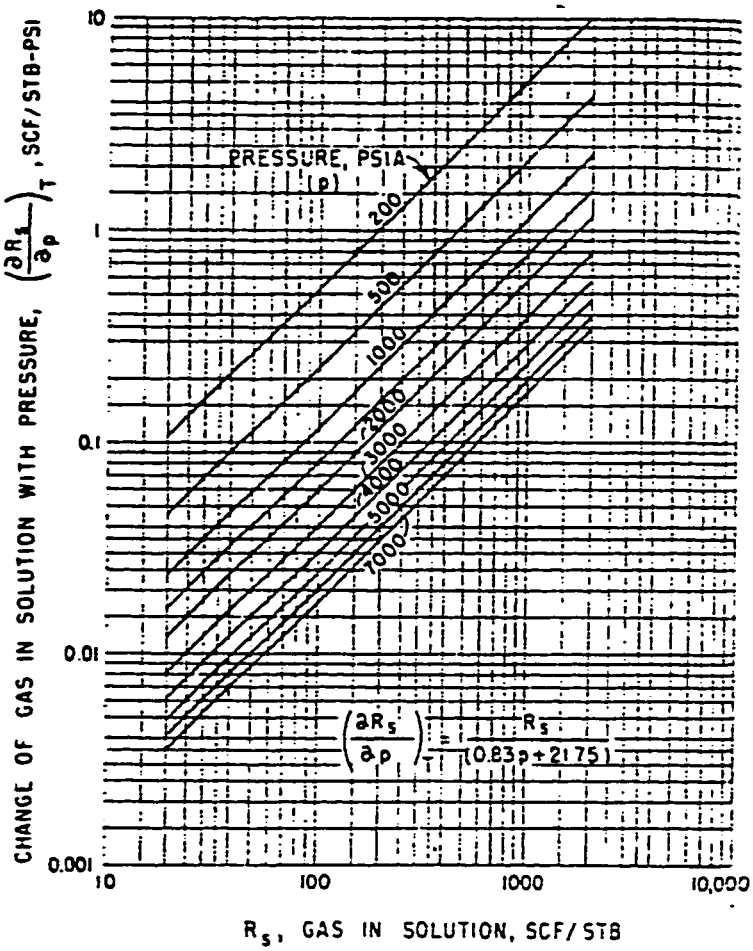


Fig.3-Change of Gas in Solution in Oil With Pressure vs. Gas in Solution. [4]

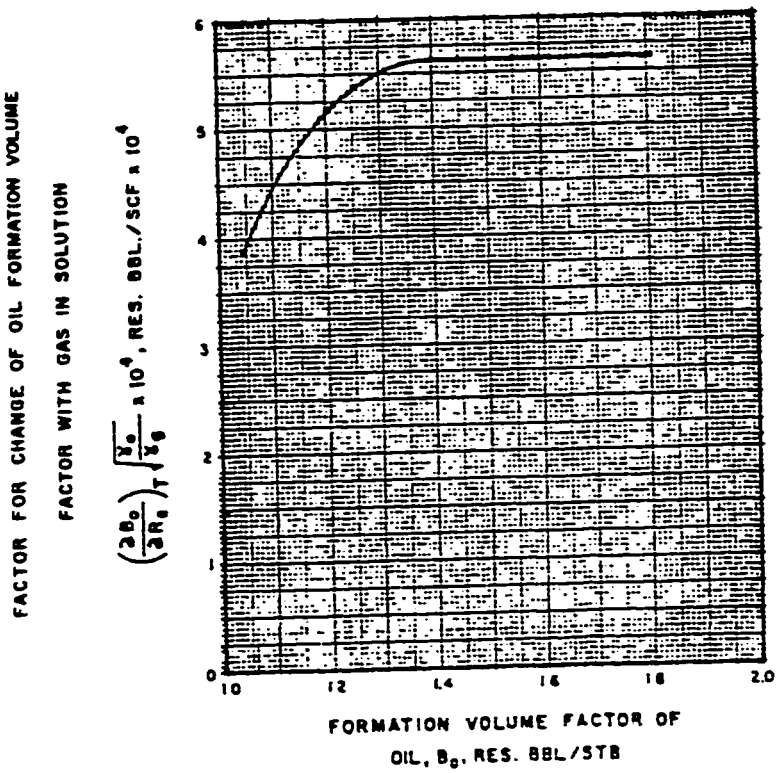


Fig.4-Change of Oil Formation Volume Factor with Gas in Solution vs. Oil Formation Volume Factor. [4]

conditions were established by calculating the second derivatives at the endpoints of the spline by means of finite difference calculus.

Their study showed that solution gas-oil ratio and gas relative density do not contribute significantly to the calculation of oil compressibility. Their correlation is presented in logarithmic form:

$$\ln(Co) = -7.573 - 1.450\ln(P) - 0.383\ln(P_b) + 1.402\ln(T) + 0.256\ln(\gamma_g) + 0.449\ln(R_{sb}) \quad (2.2)$$

The average absolute percent error of the natural log of compressibility (not the compressibility) is 4.5% with a maximum absolute error of 9.2%. This error could be higher if the compressibility was used instead of its log.

The correlation is not accurate at pressures below 500 psia or bubblepoint pressures below 763 psia. The oil compressibility values, at pressures below 500 psia, are much larger and thus this correlation yields approximate results with higher errors.

2.2 Gas Pseudo-Critical Properties

The pseudo-critical properties of the gas are usually estimated from the gas composition using Kay's mixing rules [6].

The pseudo-critical pressure of the gas mixture is calculated from:

$$P_{pc} = \sum_{i=0}^{n} y_i P_{ci} \tag{2.3}$$

The pseudo-critical temperature of the gas mixture is defined by:

$$T_{pc} = \sum_{i=0}^{n} y_i T_{ci} \tag{2.4}$$

where

P_{pc} = the gas pseudo-critical pressure

T_{pc} = the gas pseudo-critical temperature

y_i = the mole fraction of component i in the gaseous state

P_{ci} = the critical pressure of component i

T_{ci} = the critical temperature of component i, and

n = the total number of components in the gaseous state

Table 1 shows the physical properties of pure gases [7]. However, if the gas composition is not available which is the case in the differential tests, the pseudo-critical properties may be estimated from

Table 1: PHYSICAL CONSTANTS FOR PURE GASES*

Component	Relative Density (Air =1.0)	Critical Pressure (psia)	Critical Temperature (^{0}F)
Methane	0.5539	666.4	-116.67
Ethane	1.0382	706.5	89.92
Propane	1.5226	616.0	206.06
Isobutane	2.0068	527.9	274.46
n-Butane	2.0068	550.6	305.62
Isopentane	2.4912	490.4	369.10
n-Pentane	2.4912	488.6	385.80
n-Hexane	2.9755	436.9	453.60
n-Heptane	3.4598	396.8	512.70
n-Octane	3.9441	360.7	564.22
n-Nonane	4.4284	331.8	610.68
n-Decane	4.9127	305.2	652.00
Carbon Dioxide	1.5196	1071.0	87.91
Hydrogen Sulfide	1.1767	1300.0	212.45
Nitrogen	0.9672	493.1	-232.51

* From Engineering Data Book [7]

existing correlations [8,9] with the knowledge of relative density of the gas mixture (γ_g) having negligible amount of N_2, CO_2 and H_2S.

2.2.1 Standing Correlations

Standing [8] presented correlations to compute the pseudo-critical pressure and temperature from relative density of a hydrocarbon gas mixture (γ_g) :

Pseudo-critical pressure,

$$P_{pc} = 677.0 + 15.0\,\gamma_g - 37.5\,\gamma_g^2 \qquad (2.5)$$

Pseudo-critical temperature,

$$T_{pc} = 168.0 + 325.0\,\gamma_g - 12.5\,\gamma_g^2 \qquad (1.7)$$

These correlations were based on gas analysis collected from California gases which represent surface traps gases and stock-tank vapors.

2.2.2 Thomas et al. Correlations

Thomas et al. [9] also presented similar correlations to compute these properties of the gas:

Pseudo-critical pressure,

$$P_{pc} = 709.604 - 58.718\,\gamma_g \tag{2.7}$$

Pseudo-critical temperature,

$$P_{Tc} = 170.491 + 370.344\,\gamma_g \tag{2.8}$$

This work was based on 84 casing head gas wells from the Phillips Natural Gas and Gasoline Department. The allowable limits of impurities for these equations (2.7 & 2.8) are 3 percent hydrogen sulfide (H_2S), 5 percent nitrogen (N_2), or a total impurity content of 7 percent. Outside these limits, the errors in pseudo-critical pressure exceed 6 percent.

2.2.3 Wichert and Aziz Adjustment Factor

For sour natural gases, the Standing-Katz chart [10] or any other Z-factor correlations may be used with appropriate adjustment of the pseudo-critical pressure and temperature. Wichert and Aziz [11] developed adjustment factors for different types of Z-factor correlations. The adjustment factor for Standing-Katz Z-factor chart (Fig. 5) is given by:

$$\varepsilon_3 = 120(A^{0.9} - A^{1.6}) + 15(B^{0.5} - B^5) \tag{2.9}$$

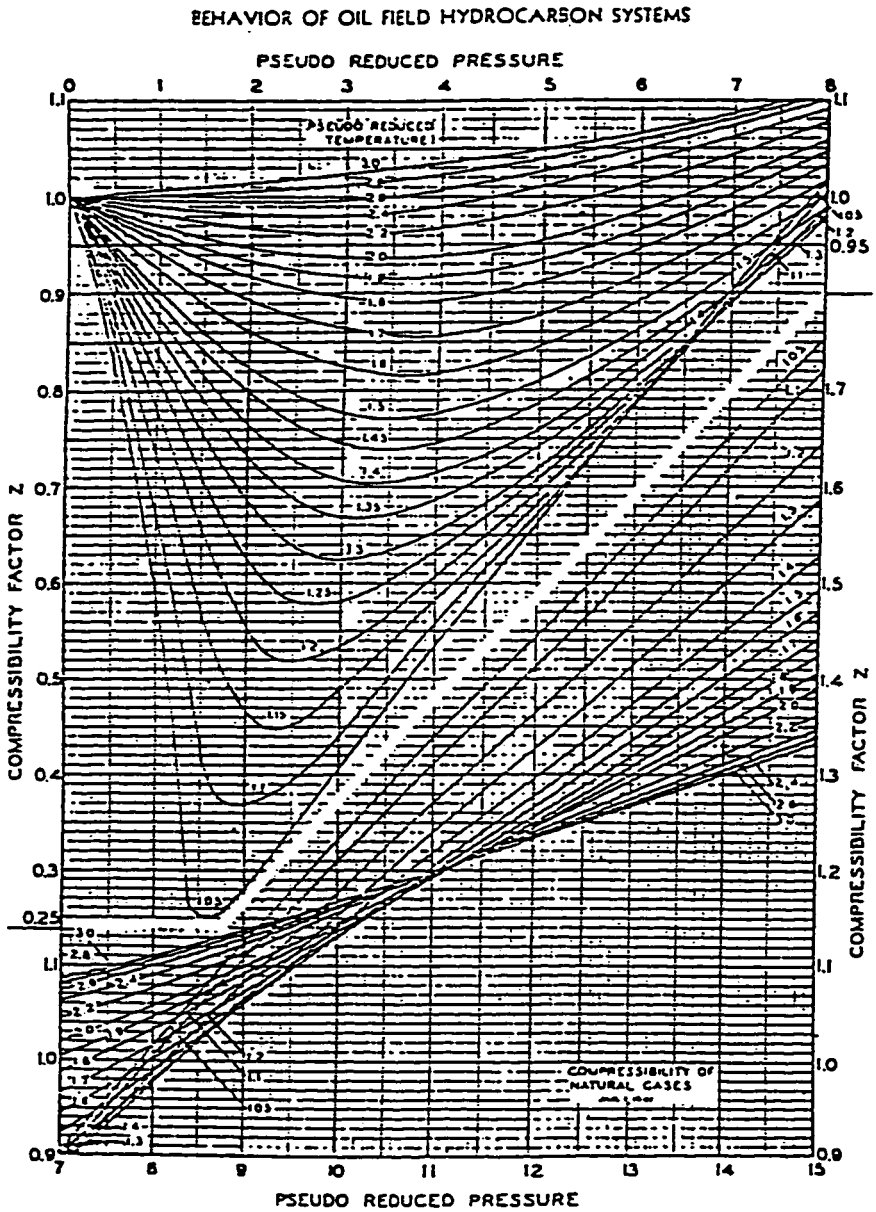


Fig.5-Compressibility Factors for Natural Gases [10]

where

ε_3 = the adjustment factor

A = the sum of mole fractions of CO_2 and H_2S

B = the mole fraction of H_2S

The adjusted pseudo-critical temperature and pressure are as follows:

$$P'_{Tc} = P_{Tc} - \varepsilon_3 \tag{2.10}$$

$$P'_{Pc} = \frac{P_{Pc} P_{Tc}}{P_{Tc} + B(1 - B)\varepsilon_3} \tag{2.11}$$

where

P'_{Tc} is the adjusted pseudo-critical temperature and P'_{Pc} is the adjusted pseudo-critical pressure.

CHAPTER 3

Chapter 3

DATA ACQUISITION

3.1 Laboratory Analysis

Laboratory analysis of a hydrocarbon sample generally provides data on PVT properties such as B_o, B_g, R_s, oil and gas viscosities, oil compressibility, and the compositional analysis of the sample. The sample is maintained at reservoir temperature and may be confined by mercury to control the pressure. The pressure is reduced below the bubblepoint, P_b, by withdrawing mercury and allowing the sample to expand and gas to evolve. Gas liberation can occur by two processes, flash and differential. The basic difference between the flash and differential processes is that the overall composition of the sample remains constant throughout the flash process while during the differential process the gas evolved, due to pressure drop, is removed from the system after each step and hence the gas composition changes.

3.1.1 Differential Liberation Process

In a differential test, the gas evolved was withdrawn from the oil at each of several pressure levels. The volume of oil and its dissolved gas at P_b are known and are the basis for comparing oil volumes at other

pressure levels. Pressure is reduced below P_b to a predetermined level and time is allowed for the gas and oil to reach equilibrium at this pressure. All of the gas is displaced with mercury while maintaining the pressure constant at this level. The volume of gas removed and the volume of oil remaining are measured and recorded along with pressure level and gas relative density. The procedure is repeated by dropping the pressure to another level. The test is generally terminated at a pressure of 0 psig. The oil volume at 0 psig is generally given at reservoir temperature and at 60 °*F*.

The differential process can be further explained by Fig. 6 which is a schematic representation of the testing procedure. During these tests, the sample in the test cell is maintained at reservoir temperature. Figure 6-(A) shows the sample at a pressure considerably above its bubblepoint of 1500 psig (Fig. 6-B). Figure 6-(C-1) shows the gas space created when pressure is reduced below the bubblepoint to 1350 psig, but the gas has been displaced by mercury, Fig. 6-(C-2). Figure 6-(D-1) shows the gas evolved when pressure is reduced from 1300 to 1200 psig, and Fig. 6-(D-2) shows the oil volume at 1200 psig.

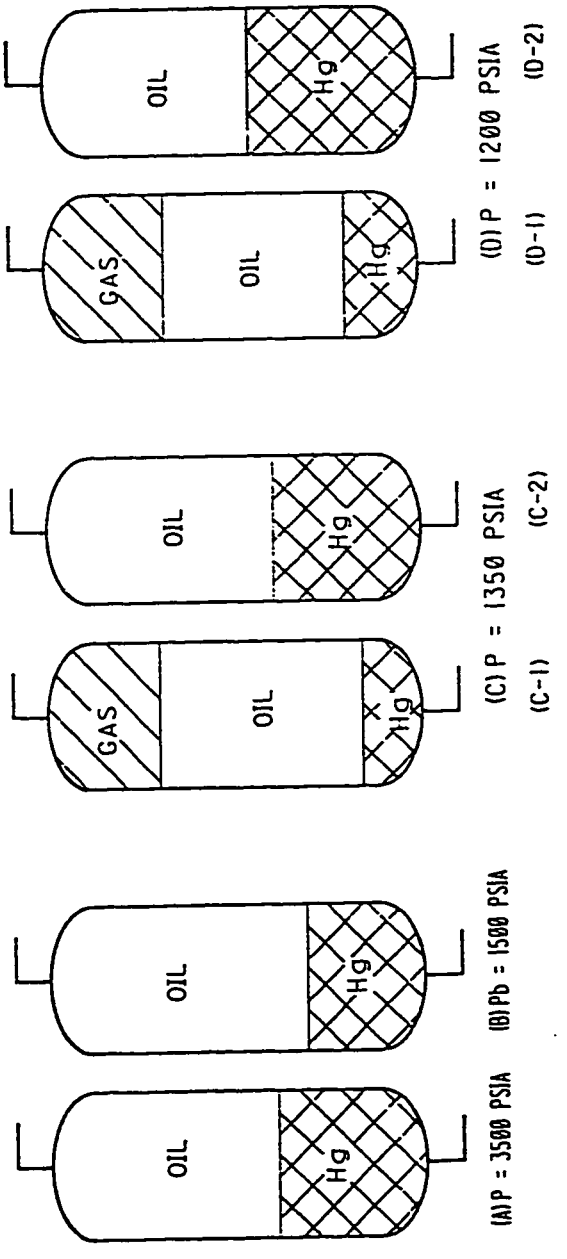
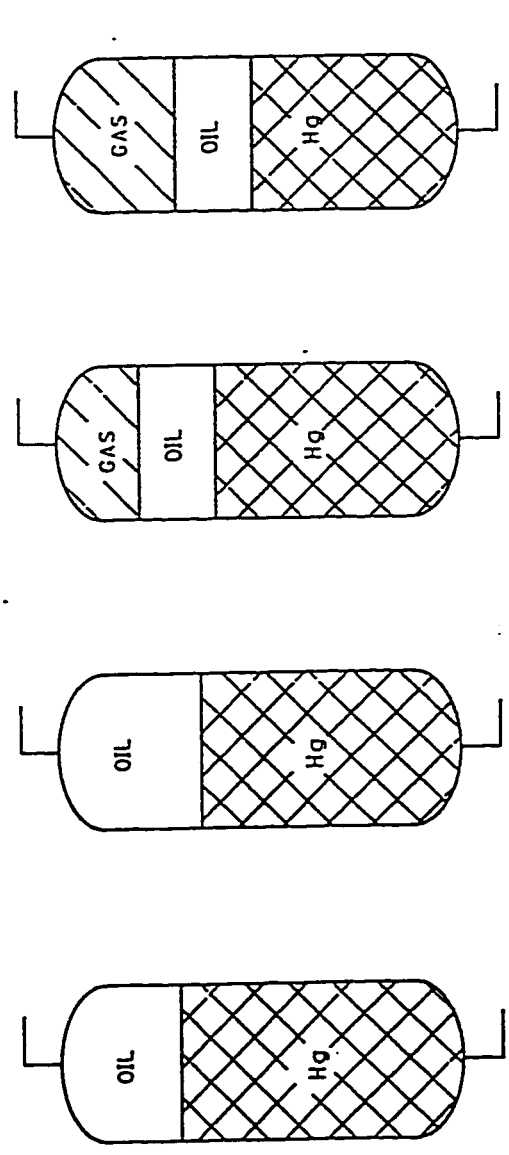


Fig.6-Differential Liberation Process.

3.1.2 Flash Liberation Process

In the flash liberation process, the overall composition of the sample remains constant throughout the test. As in the differential process, the oil volume at P_b and reservoir temperature is used as the reference for volumes at other pressures. Pressure is dropped to a predetermined level (100 psig below P_b) to permit gas to be evolved, and enough time is allowed for oil and gas to reach equilibrium. The pressure level and the total volume of oil and gas are recorded. If a visual cell is used, the oil volume can be determined as well as the total volume. The gas is not removed, and pressure is further reduced by about 100 to 200 psi and the total volume is recorded at that pressure. At the end of the test, pressure is reduced to 0 psig and the total volume of liberated gas is measured. The oil volume at 0 psig is measured at 60 °F to provide the stock-tank oil volume factor. Figure 2 is a schematic that depicts several pressure stages during a flash differential sample analysis. The sample has P_b of 1500 psig and Figs. 7-(A and B) show the sample at pressures above P_b and at P_b, respectively. Figures 7-(C and D) show the volumes of gas and oil that result at pressures below P_b.



(A) P = 3500 PSIA (B) Pb = 1500 PSIA (C) P = 1350 PSIA (D) P = 1200 PSIA

Fig.7-Flash Liberation Process.

From all these tests, however, the oil compressibility below P_b pressure cannot be measured directly and thus requires tedious calculations from these data.

3.1.3 Flash Separation Tests

A flash separation test on hydrocarbon sample determines the B_{oi}, R_{si} and stock-tank oil gravity values that will result if reservoir fluid is produced through a specific set of surface separation conditions. Several sets of separator conditions can be run to determine the optimum separator conditions.

3.2 Data Preparation for Analysis

3.2.1 Gas Pseudo-Critical Properties

This study used 145 sets of gas analysis to generate the new pseudo-critical pressure and temperature correlations. The gas samples were collected from separator tests and stock-tank vapors of the Middle East. Table 2 presents the range of the data.

The gas pseudo-critical properties were calculated based on Kay's mixing rules [6] which were presented earlier.

Table 2: SUMMARY OF DATA FOR GAS PSEUDO-CRITICAL PROPERTIES (PRESSURE AND TEMPERATURE)

Property	Minimum	Maximum	Averag	St.Dev.
Gas Mixture Relative Density, Air=1	0.676	1.745	1.112	0.320
Gas Pseudo-Critical Pressure, psia	586.9	676.5	648.008	21.233
Gas Pseudo-Critical Temperature, °R	383.9	690.8	519.382	96.555
Nitrogen (N_2)	0.0	2.6	0.334	0.540
Carbon Dioxide (CO_2)	0.0	2.0	1.034	0.468
Hydrogen Sulfide (H_2S)	0.0	0.9	0.021	0.129

3.2.2 Oil Isothermal Compressibility At and Below Bubblepoint Pressure

This study utilized 2635 data points from 372 gas differential liberation tests collected from the Middle East and North America oil fields. Table 3 presents the range of the data.

3.2.2.1 Estimation of B_o and R_s Derivatives

Oil compressibility values were calculated with Eq. (2.1) using differential data. Unlike McCain et al. [5], the derivatives in Eq. (2.1) were estimated using numerical differentiation using Lagrangian [12] interpolation formulas. A simple example can be used to illustrate how numerical differentiation formulas can be obtained from Lagrangian interpolation formulas. Suppose that a second-order approximating polynomial of the form:

$$y(x) = \left[\frac{(x-x_1)(x-x_2)}{(x_0-x_1)(x_0-x_2)}\right] y_0 + \left[\frac{(x-x_0)(x-x_2)}{(x_1-x_0)(x_1-x_2)}\right] y_1 + \left[\frac{(x-x_0)(x-x_1)}{(x_2-x_0)(x_2-x_1)}\right] y_2 \qquad (3.1)$$

Table 3: SUMMARY OF DATA FOR OIL ISOTHERMAL COMPRESSIBILITY AT AND BELOW BUBBLEPOINT PRESSURE

Property	Minimum	Maximum	Average	St. Dv.
Temperature, ^{o}F	82.000	300.000	196.409	31.048
Bubblepoint Pressure, psia	147.000	4477.000	1896.616	819.692
Pressure, psia	100.000	4477.000	956.500	702.292
Gas-Oil Ratio, R_{sb} (SCF/STB)	30.000	4322.000	673.774	381.625
Gas Relative Density, Air-=1	0.657	1.876	1.124	0.169
Oil API Gravity, ^{o}API	18.800	49.200	32.556	4.158
Oil Compressibility, psi^{-1}	0.797E-04	0.255E-01	0.169E-02	0.286E-02

is arranged so as to pass through three adjacent points, (x_0,y_0), (x_1,y_1), and (x_2,y_2). The first derivative of this expression is:

$$\frac{\partial y}{\partial x} = \left[\frac{(2x-x_1-x_2)}{(x_0-x_1)(x_0-x_2)}\right] y_0 + \left[\frac{(2x-x_0-x_2)}{(x_1-x_0)(x_1-x_2)}\right] y_1 + \left[\frac{(2x-x_0-x_1)}{(x_2-x_0)(x_2-x_1)}\right] y_2 \qquad (3.2)$$

If this formula is evaluated at $x = x_0$, the result will be an expression for the first derivative based on forward differences. If the formula is evaluated at $x = x_1$, the result will be an expression for the first derivative based on central differences. If the formula is evaluated at $x = x_2$, the result will be an expression for the first derivative based on backward differences.

Central difference formulas are more accurate than forward or backward difference formulas; however, for some applications, central difference formulas cannot be used. An example of this situation occurs at the beginning and end of a set of data points.

3.2.2.2 Estimation of Oil Isothermal Compressibility At Bubblepoint Pressure

The bubblepoint oil isothermal compressibility can be defined by two means. The first method is by defining it from above the bubblepoint by taking the limit of Eq. (1.1) as the pressure approaches the bubblepoint. The second method is by defining it from below the bubblepoint by taking the limit of Eq. (1.2) as the pressure approaches the bubblepoint. In our case, the second method was used to define this bubblepoint compressibility, since the data, used in this study, are below bubblepoints.

3.2.2.3 Z-Factor

The Z-factor, used in the computation of B_g, was computed with Dranchuck et al. [13] routine. Since the Z-factor is a function of reduced pressure and temperature, the critical pressure and temperature were calculated using the new correlations developed in this work.

3.2.2.4 Data Base

The data base consisted of values of reservoir temperature, bubblepoint pressure (P_b), reservoir pressure, solution gas-oil ratio (R_{sb}) at bubblepoint conditions, stock-tank oil gravity, gas relative density at bubblepoint conditions, and oil compressibility values at and below bubblepoint.

CHAPTER 4

Chapter 4

REGRESSION THEORY AND ANALYSIS

4.1 Regression Theory [14]

The basic concept of regression analysis is to produce a linear or nonlinear combination of independent variables that will correlate as closely as possible with the dependent variable.

4.1.1 Linear Multiple Regression

Consider a set of observations of size n_d on which the properties $y, x_1, x_2 \ldots\ldots x_n$ are measured. The x's and y are the independent and dependent variables, respectively. The linear regression equation of y on x's can be written as:

$$y = a_0 + a_1x_1 + a_2x_2 + \ldots. + a_nx_{n_d} \qquad (4.1)$$

which represents a hyperplane in (n+1) dimensional space. Equation (4.1) can be written for any observation point i as:

$$y_i = a_0 + a_1 x_{i1} + a_2 x_{i2} + \ldots + a_n x_{in_d} \; ; \; i = 1, n_d \tag{4.2}$$

The n_d equations for the n_d experimental measurements can be expressed in matrix form as:

$$\begin{bmatrix} 1 & x_{11} & x_{12} & \cdots & x_{1n} \\ 1 & x_{21} & x_{22} & \cdots & x_{2n} \\ 1 & x_{31} & x_{32} & \cdots & x_{3n} \\ . & . & . & & . \\ . & . & . & & . \\ . & . & . & & . \\ 1 & x_{n_d 1} & x_{n_d 2} & \cdots & x_{n_d n} \end{bmatrix} \begin{bmatrix} a_0 \\ a_1 \\ a_2 \\ . \\ . \\ . \\ a_n \end{bmatrix} = \begin{bmatrix} y_1 \\ y_2 \\ y_3 \\ . \\ . \\ . \\ y_n \end{bmatrix} \tag{4.3}$$

or on simpler form

$$X\vec{a} = \vec{y} \tag{4.4}$$

where

$X = n_d \times (n+1)$ matrix

$\vec{a} = (n+1)$ vector

$\vec{y} = n_d$ vector

n = total number of independent variables

Therefore, the objective is to solve for the vector $\vec{a}$ for which $X\vec{a}$ is as close as possible to vector $\vec{y}$ since the exact solution cannot be found. Such a vector is the least-squares solution. The unique least-squares solution to this system presented in Eq. (4.4) is:

$$\hat{a} = (X^T X)^{-1} X^T \vec{y} \tag{4.5}$$

where

$\hat{a}$ is the least-squares solution to the system $X\vec{a}=\vec{y}$ and X^T is the transpose of matrix X.

4.1.2 Nonlinear Multiple Regression

This type of regression can be achieved by reducing the non-linear relationship to a linear one by appropriating transformation of variables. For example, the following non-linear model:

$$C = a_0' P^{a1} R^{a2} T^{a3} G^{a4} \tag{4.6}$$

can be linearized by taking the log of both sides,

$$\log C = \log(a_0') + a_1\log(P) + a_2\log(R) + a_3\log(T) + a_4\log(G) \quad (4.7)$$

to obtain:

$$y = a_0 + a_1x_1 + a_2x_2 + a_3x_3 + a_4x_4 \quad (4.8)$$

where

$y = \log(C)$

$a_0 = \log(a_0')$

$x_1 = \log(P)$

$x_2 = \log(R)$

$x_3 = \log(T)$ and

$x_4 = \log(G)$

Equation (4.8) can be solved by the method of linear multiple regression, as outlined earlier.

4.2 Error Analysis

Statistical and graphical error analysis were used to check the accuracy and performance of the correlations developed in this study.

4.2.1 Statistical Error Analysis

Various statistical means were used to determine the accuracy of the correlations relative to the actual or measured values. These statistical means were average percent relative error, average absolute percent relative error, minimum/maximum absolute percent relative error, standard deviation, and the correlation coefficient.

4.2.1.1 Average Percent Relative Error

It is an indication of the relative deviation in percent from the measured values and is given by:

$$E_r = (1/n_d)\sum_{i=1}^{n_d} E_i \tag{4.9}$$

where E_i is the relative deviation in percent of an estimated value from measured value and it is given by:

$$E_i = 100\left[\frac{(x_m - x_e)}{x_m}\right]_i, i = 1, 2...n_d \tag{4.10}$$

where x_e and x_m represent the estimated and measured values, respectively. The lower the value of E_r, the more equally distributed are the errors between positive and negative values.

4.2.1.2 Average Absolute Percent Relative Error

It is defined as:

$$E_a = (1/n_d)\sum_{i=1}^{n_d} |E_i| \tag{4.11}$$

and indicates the relative absolute deviation in percent from the measured values. A lower value of E_a, implies a better correlation.

4.2.1.3 Minimum/Maximum Absolute

Percent Relative Error

Following the calculation of absolute percent relative error for each point, $|E_i|, i = 1,2 \ldots n_d$, both the minimum and maximum values are obtained to find the range of error for each correlation:

$$E_{min} = \min_{i=1}^{n_d} |E_i| \tag{4.12}$$

$$E_{max} = \max_{i=1}^{n_d} |E_i| \tag{4.13}$$

The accuracy of a correlation can be examined by maximum absolute percent relative error. The accuracy of the correlation also increases with lower value of maximum absolute relative error.

4.2.1.4 Standard Deviation

Standard deviation is a measure of dispersion and it is expressed as:

$$s = \sqrt{(E_i - E_r)^2/(1 - n_d)} \tag{4.14}$$

where n_d is the number of points. A lower value of standard deviation means a smaller degree of scatter.

4.2.1.5 Correlation Coefficient

The correlation coefficient, r, represents the degree of success in reducing the standard deviation by regression analysis. It is defined as [15]:

$$r^2 = 1 - |\sum_{i=1}^{nd}(x_m - x_r)_i^2 / \sum_{i=1}^{nd}(x_m - \bar{x})_i^2| \tag{4.15}$$

where $\bar{x}$ is the average value of x_m and is defined as:

$$\bar{x} = (1/n_d)\sum_{i=1}^{n_d}(x_m)_i \qquad (4.16)$$

The correlation coefficient lies between 0 and 1. A value of 1 indicates a perfect correlation, whereas a value of of 0 implies no correlation at all among the given independent variables.

4.2.1.6 Student's T-Distribution

This statistic test is an application of null hypothesis where each parameter in the model being tested is assumed to be zero. This is computed as regression coefficient divided by its standard error [16]. High T value indicates a good estimte of the parameter. The other item associated to this test is the probability that T would obtain a greater absolute value than that observed given that the true parameter is zero. This is two-tailed significance probability.

4.2.2 Graphical Error Analysis

Graphical means help in visualizing the accuracy of a correlation. Two graphical analysis techniques were used and presented below.

4.2.2.1 Crossplot

A crossplot is a plot of one variable obtained by two different means. A 45° straight line is drawn on this plot to reflect the perfect correlation line on which the estimated and measured are equal. Then, all estimated values are plotted versus the measured values to form a crossplot. The closer the plotted data points to the 45° line, the better the correlation is.

4.2.2.2 Incremental Analysis

In this analysis, the data are grouped within specific ranges of certain parameter that mostly influence the correlation. The statistical results of each group predicted by the correlation can show the strengths and weaknesses of the correlation besides the cumulative overall results of the correlation.

CHAPTER 5

Chapter 5

DEVELOPMENT OF CORRELATIONS

5.1 Gas Pseudo-Critical Properties

Previous research [8,9] and Figs. 8 and 9 suggested that hydrocarbon gas pseudo-critical properties are functions of their relative densities. Moreover, multiple regression analysis revealed that hydrocarbon gases pseudo-critical properties can be fitted with their relative densities using linear models and hence the following models were found to be the most applicable and representative models for the gas pseudo-critical pressure and temperature:

$$P_{pc} = a_0 + a_1 \gamma_g^{1/2} + a_2 \gamma_g \qquad (5.1)$$

$$T_{pc} = a_0 + a_1 \gamma_g^{1/2} \qquad (5.2)$$

where the a_i's represent the regression coefficients.

Tables 4 and 5 show regression T-statistics values and regression coefficients.

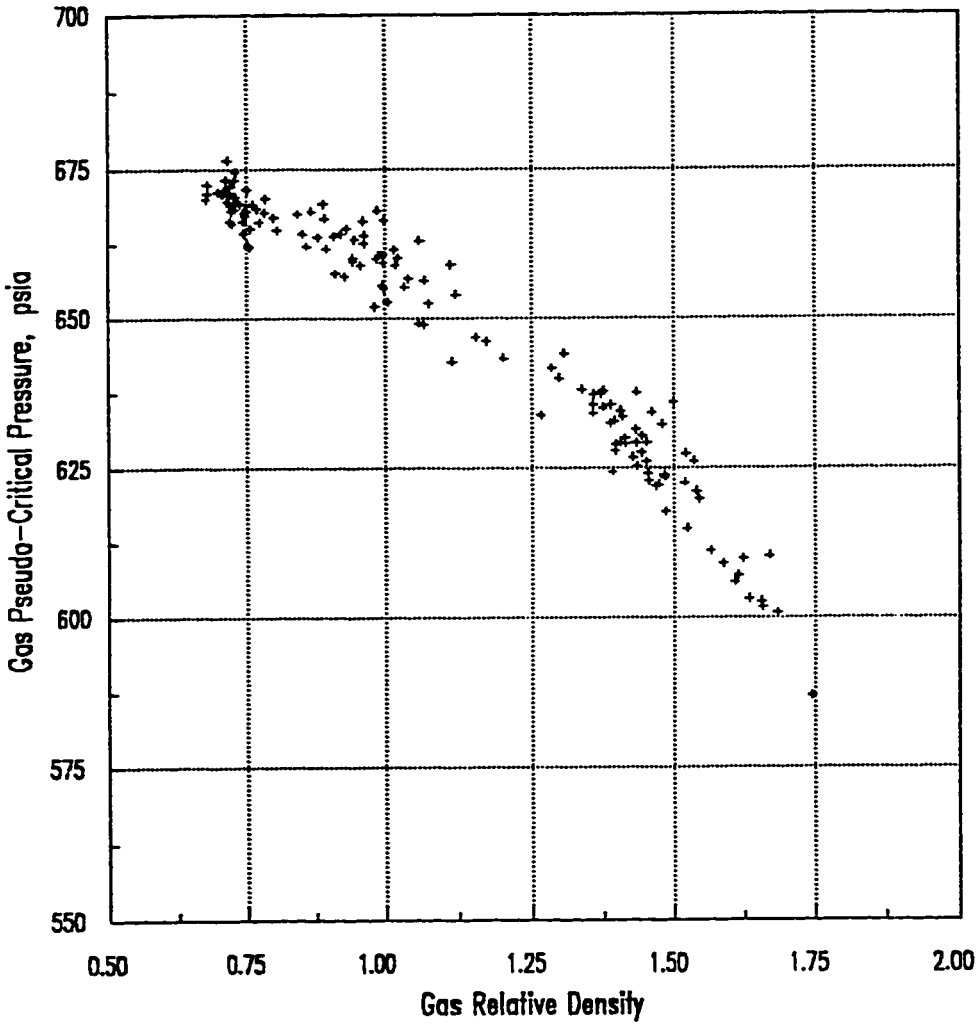


Fig. 8 - Scatter Diagram Of Gas Pseudo-Critical Pressure Data

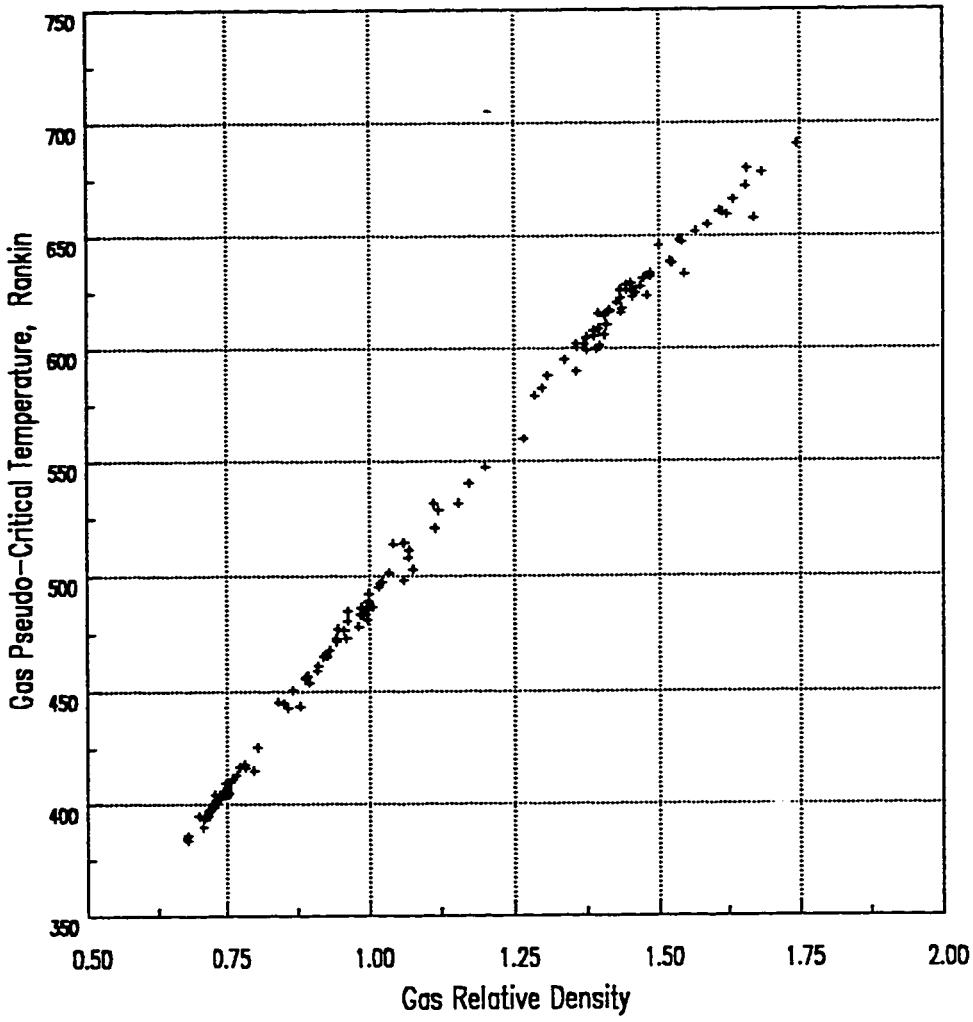


Fig. 9- Scatter Diagram Of Gas Pseudo-Critical Temperature Data

Table 4: T-STATISTICS TEST FOR THE REGRESSION COEFFICIENTS OF GAS PSEUDO-CRITICAL PRESSURE AND TEMPERATURE CORRELATIONS

Independent Variable	T-Values	
	Pressure	Temperature
Intercept	22.043	-50.924
$\gamma_g^{1/2}$	10.290	239.950
γ_g	-13.403	-

Table 5: REGRESSION COEFFICIENTS FOR GAS PSEUDO-CRITICAL PRESSURE AND TEMPERATURE CORRELATIONS

Independent Variable	Coefficients	
	Pressure	Temperature
Intercept	490.68315	-141.79467
$\gamma_g^{1/2}$	443.81304	633.48531
γ_g	-274.99261	-

5.2 Oil Isothermal Compressibility At and Below Bubblepoint Pressure

Non-linear simple/multiple regression analysis were used to develop a correlation for oil isothermal compressibility at and below bubblepoint pressure. Previous research [4,5] indicated that this oil compressibility is a function of the solution gas-oil ratio at bubblepoint conditions, stock-tank oil gravity, bubblepoint pressure, reservoir temperature and pressure.

Evaluation of the data was the first step in selecting the models. The preliminary analysis of the data was based on scatter diagrams and correlation coefficients [15]. Scatter diagrams showed some ideas about the relationship between dependent and independent variables. Correlation coefficient, however, indicated how closely related the dependent to each independent variables. Therefore, several models were tested to see the effect and combined-effect of each independent variables.

Finally, the 2635 data points of oil compressibility values at and below bubblepoint pressure were correlated with most commonly available data (pressure, bubblepoint pressure, solution gas-oil ratio at P_b conditions, reservoir temperature, gas and oil relative densities) using the following model:

$$C_{ob} = e^{a_0} P^{a_1} P_b^{a_2} R_{sb}^{a_3} T^{a_4} \gamma_g^{a_5} \gamma_o^{a_6} e^{a_7(P-P_b)} \quad (5.3)$$

which was transformed to a linear form,

$$\ln(C_{ob}) = a_0 + a_1\ln(P) + a_2\ln(P_b)$$

$$+ a_3\ln(R_{sb}) + a_4\ln(T) + a_5\ln(\gamma_g) + a_6\ln(\gamma_o) + a_7 \ (P - P_b) \quad (5.4)$$

where

C_{ob} = oil isothermal compressibility at and below bubblepoint pressure, psi^{-1}

P = pressure, *psia*

P_b = bubblepoint pressure, *psia*

R_{sb} = solution gas-oil ratio at P_b conditions, SCF/STB

T = reservoir temperature, $°R$

γ_g = gas relative density at P_b conditions, air = 1

γ_o = oil relative density, water = 1

$a_i's$ = regression coefficients

The T-statistics for $\ln(\gamma_o)$ indicated that, in the presence of the given variables in Eq. (5.4), oil relative density does not contribute significantly to the calculation of oil compressibility. Therefore, the above model (Eq. 5.4) was reduced to the following:

$$\ln(C_{ob}) = a_0 + a_1\ln(P) + a_2\ln(P_b) + a_3\ln(R_{sb}) + a_4\ln(T) + a_5\ln(\gamma_g) + a_6(P - P_b) \quad (5.5)$$

Tables 6 and 7 show regression T-statistics values and regression coefficients.

Table 6: T-STATISTICS TEST FOR THE REGRESSION COEFFICIENTS OF OIL ISOTHERMAL COMPRESSIBILITY AT AND BELOW BUBBLE-POINT PRESSURE CORRELATION

Independent Variable	T-Value
Intercept	-45.831
ln(P)	-695.596
$\ln(P_b)$	-11.714
$\ln(R_{sb})$	133.082
ln(T)	47.117
$\ln(\gamma_g)$	-21.628
$(P-P_b)$	82.095

Table 7: REGRESSION COEFFICIENTS FOR OIL ISOTHERMAL COMPRESSIBILITY AT AND BELOW BUBBLEPOINT PRESSURE CORRELATION

	Regression Coefficients
Intercept	-7.62576707
ln(P)	-1.72566721
$\ln(P_b)$	-0.08038085
$\ln(R_{sb})$	0.65906353
ln(T)	1.30174740
$\ln(\gamma_g)$	-0.30375873
$(P-P_b)$	0.000232984

CHAPTER 6

Chapter 6

COMPARISON OF CORRELATIONS

6.1 Gas Pseudo-Critical Properties

6.1.1 Statistical Analysis

This involves the comparison of average percent relative error, average absolute percent relative error, minimum/maximum absolute percent relative error, standard deviation, and correlation coefficient for each correlation. Results are shown in Tables 8 and 9.

This study reveals the best results for these gas pseudo-critical correlations. Both Standing's and Thomas et al.'s correlations tend to underestimate these properties.

The correlations obtained by this study also show average absolute percent error of 0.49 and 0.69 with a maximum absolute percent error of 2.24 and 2.83 for gas pseudo-critical pressure and temperature, respectively.

This study also shows high degree of correlations (0.9813 and 0.9988 for pressure and temperature, respectively). Standing's and Thomas et al.'s correlations are found to have lower degree of correlations.

Table 8: STATISTICAL ACCURACY FOR GAS PSEUDO-CRITICAL PRESSURE

Correlation	Er	Ea	Emin	Emax	r	s
Standing 1947	0.71	0.79	0.00	3.29	0.9526	0.7175
Thomas et al. 1970	0.56	0.85	0.01	3.45	0.9474	0.8939
This Study 1990	0.00	0.49	0.00	2.24	0.9813	0.6392

Table 9: STATISTICAL ACCURACY FOR GAS PSEUDO-CRITICAL TEMPERATURE

Correlation	Er	Ea	Emin	Emax	r	s
Standing 1947	1.24	1.34	0.03	4.01	0.9958	1.0223
Thomas et al. 1970	1.44	1.65	0.01	4.47	0.9950	1.2011
This Study 1990	0.00	0.69	0.00	2.83	0.9988	0.8977

6.1.2 Crossplots

The crossplots of estimated versus observed values of gas pseudo-critical properties are shown in Figs. 10 through 15.

The scattered diagram of gas pseudo-critical pressure data points obtained by this study are very close to the perfect correlation 45° line. Data points from Standing's and Thomas et al.'s correlations fall below the 45° line. Thomas et al.'s correlation overestimates pseudo-critical pressure at pressure values lower than 625 psia.

The crossplot of gas pseudo-critical temperature correlation for this study fall on the 45° line which indicates excellent correlation. The data points obtained from Standing's and Thomas et al.'s correlations, however, fall below the 45° line.

Figures 16 and 18 show comparison plots of gas pseudo-critical pressure and temperature for all correlations with the raw data whereas Figs. 17 and 19 compare the correlations with pure hydrocarbon gases outside data range.

6.1.3 Incremental Analysis

This study and existing correlations were evaluated within specific ranges of gas relative density since it has a great influence on gas properties. The statistical results are shown in Tables 10 and 11 and

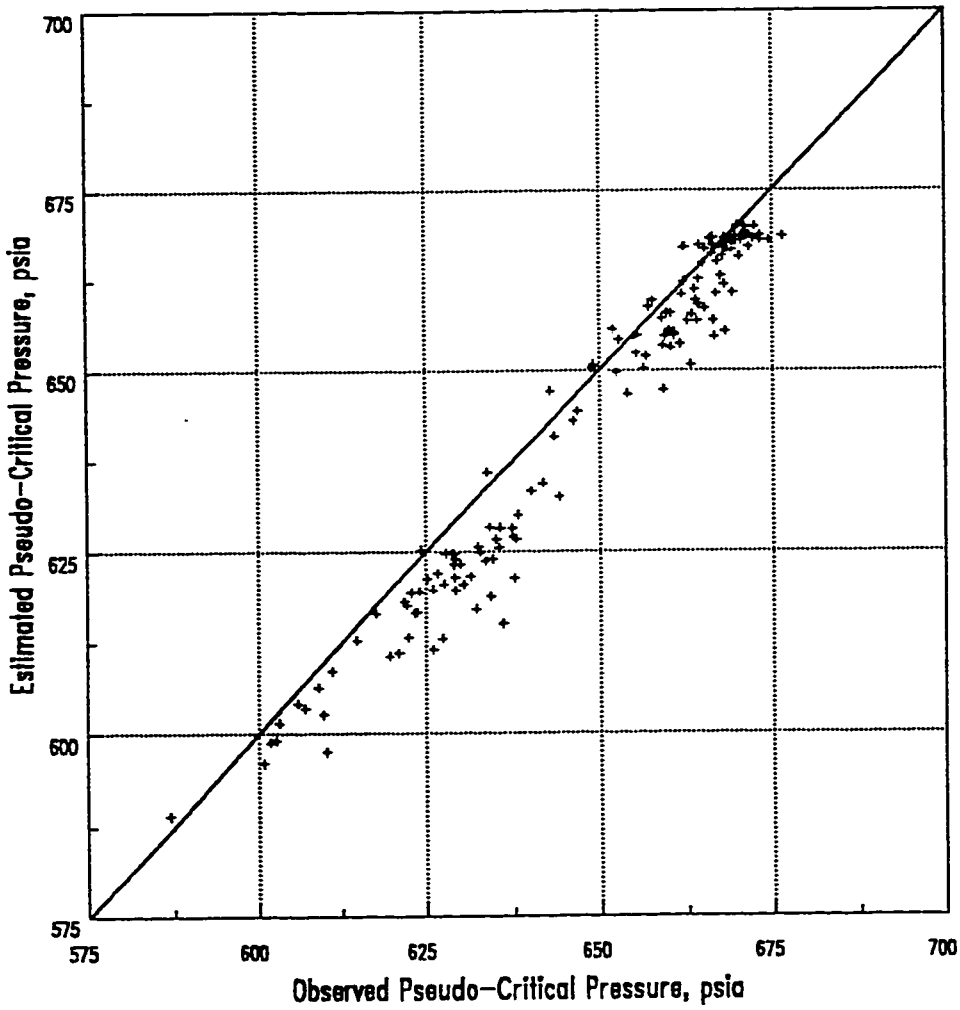


Fig. 10- Crossplot For Gas Pseudo-Critical Pressure (Standing)

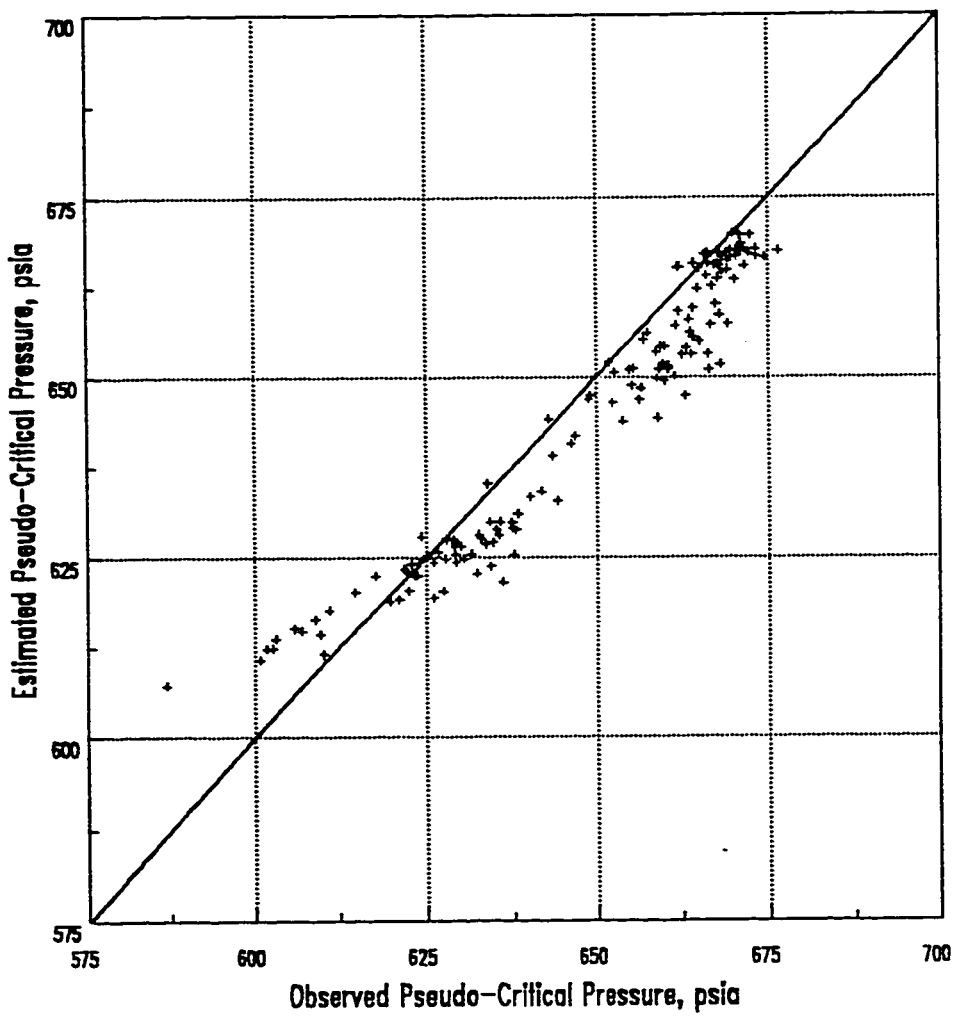


Fig. 11- Crossplot For Gas Pseudo-Critical Pressure (Thomas et al)

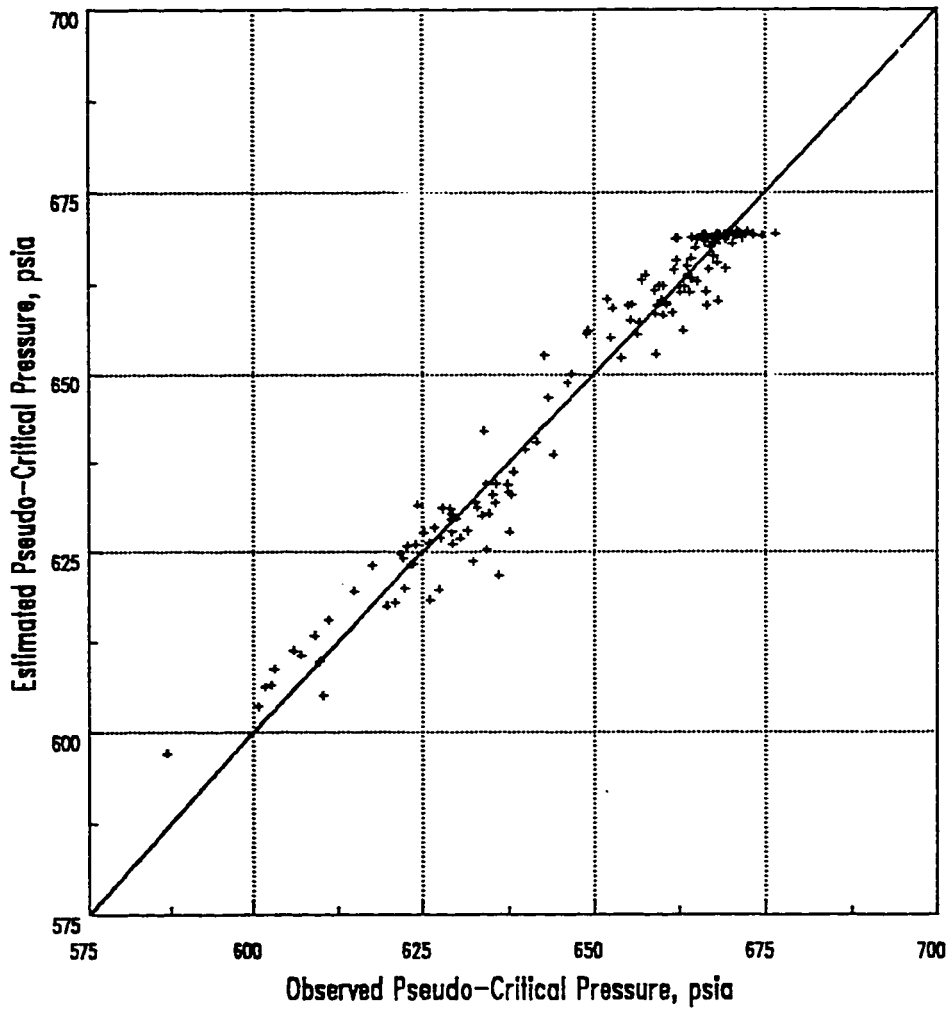


Fig. 12 - Crossplot For Gas Pseudo-Critical Pressure (This Study)

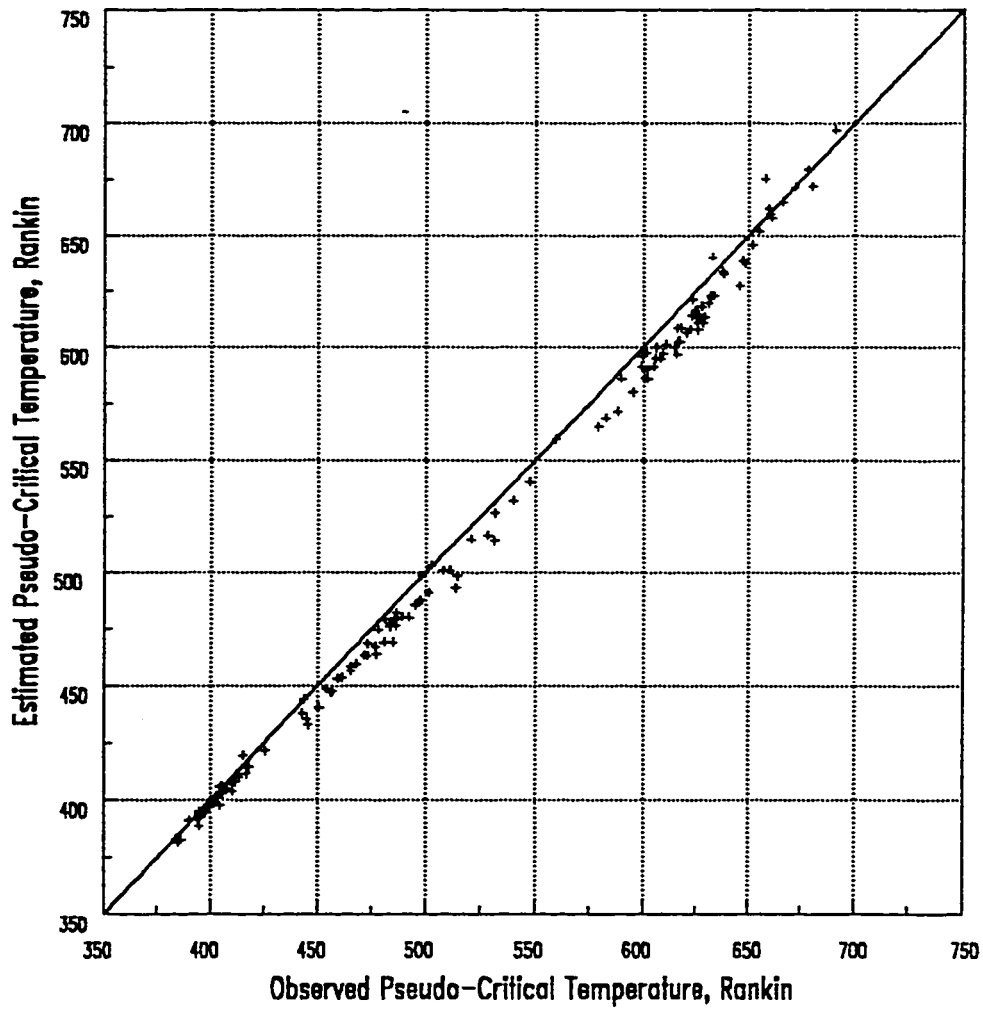


Fig. 13- Crossplot For Gas Pseudo-Critical Temperature (Standing)

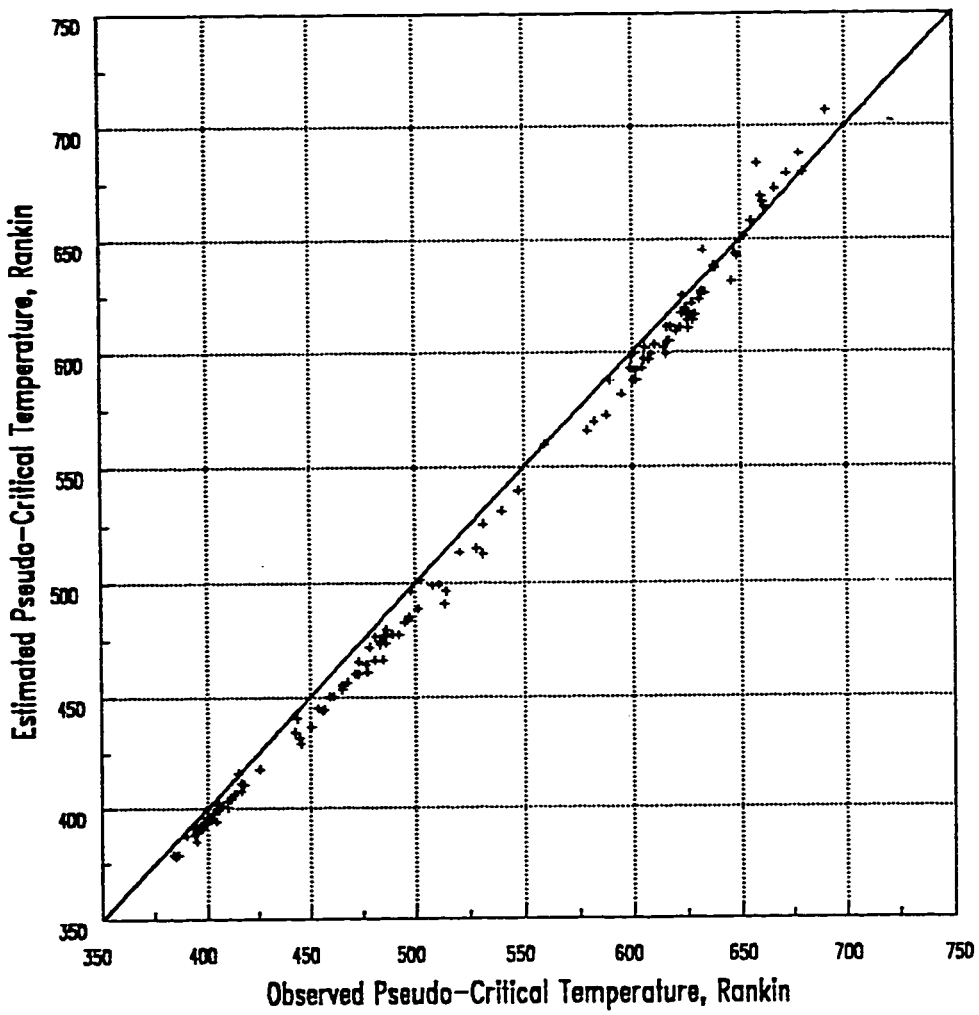


Fig. 14 - Crossplot For Gas Pseudo-Critical Temperature (Thomas et al)

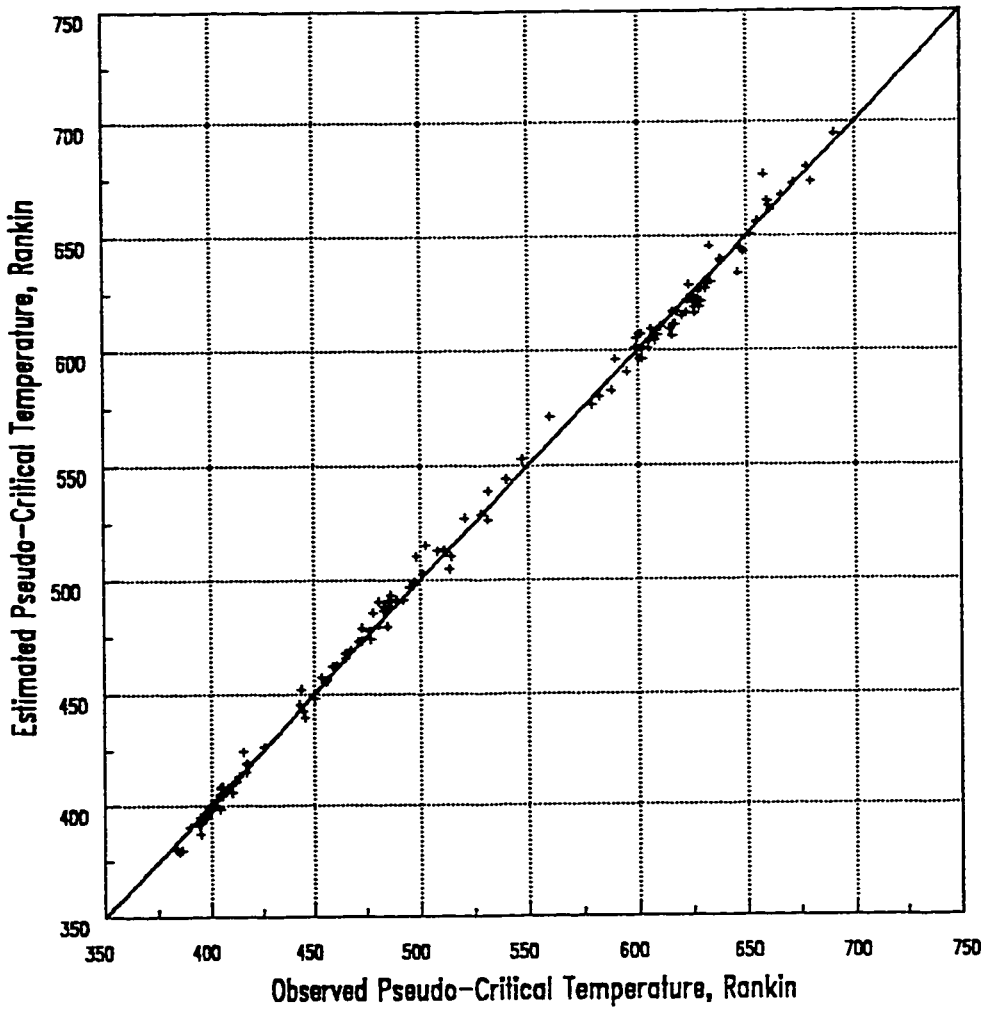


Fig. 15 - Crossplot For Gas Pseudo-Critical Temperature (This Study)

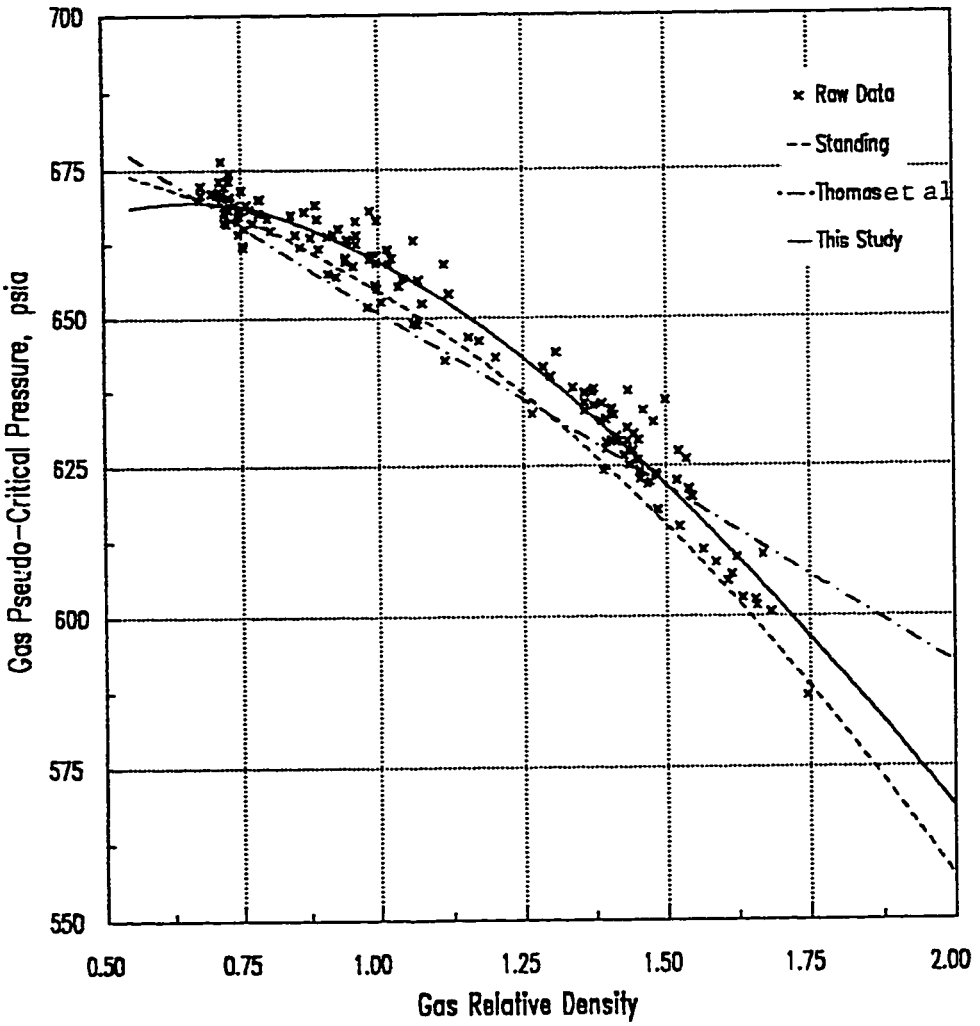


Fig. 16 - Comparison Plot For Gas Pseudo-Critical Pressure

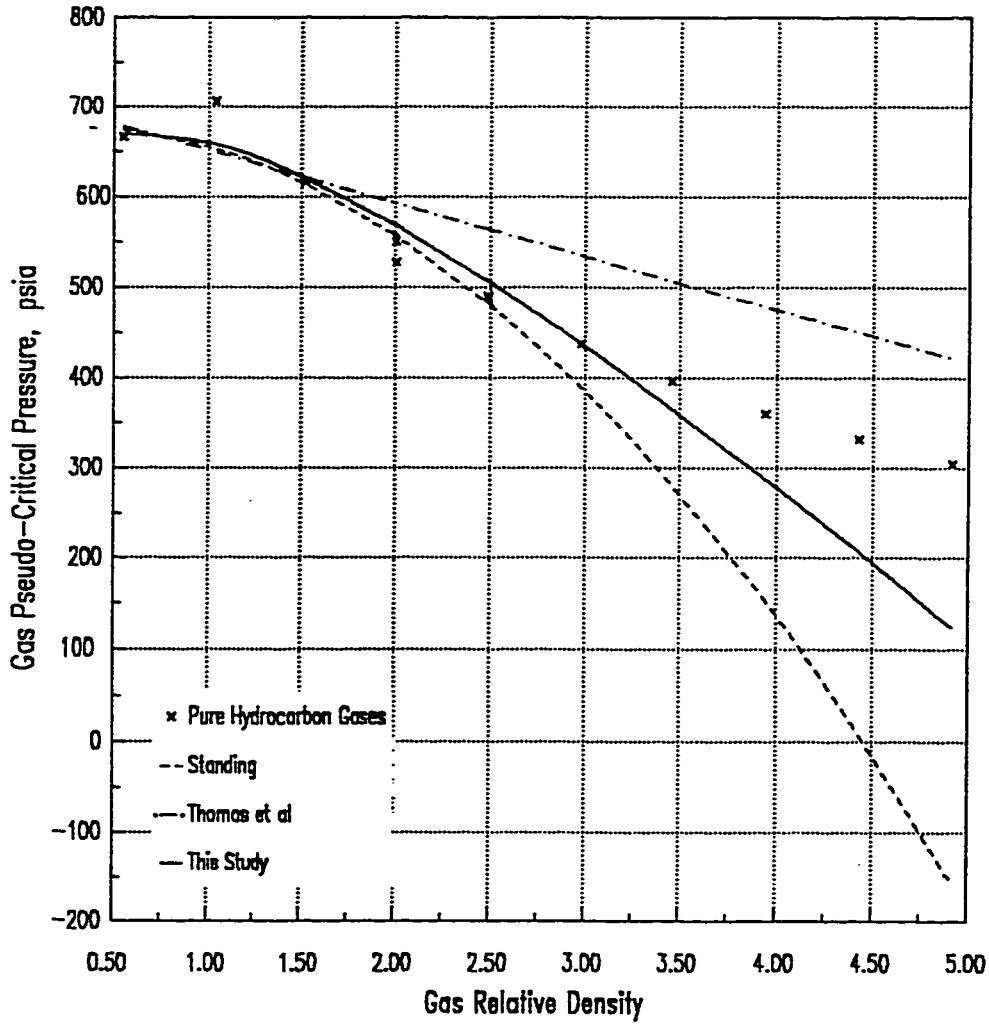


Fig. 17- Comparison Plot For Gas Pseudo-Critical Pressure with Pure Hydrocarbon Gases

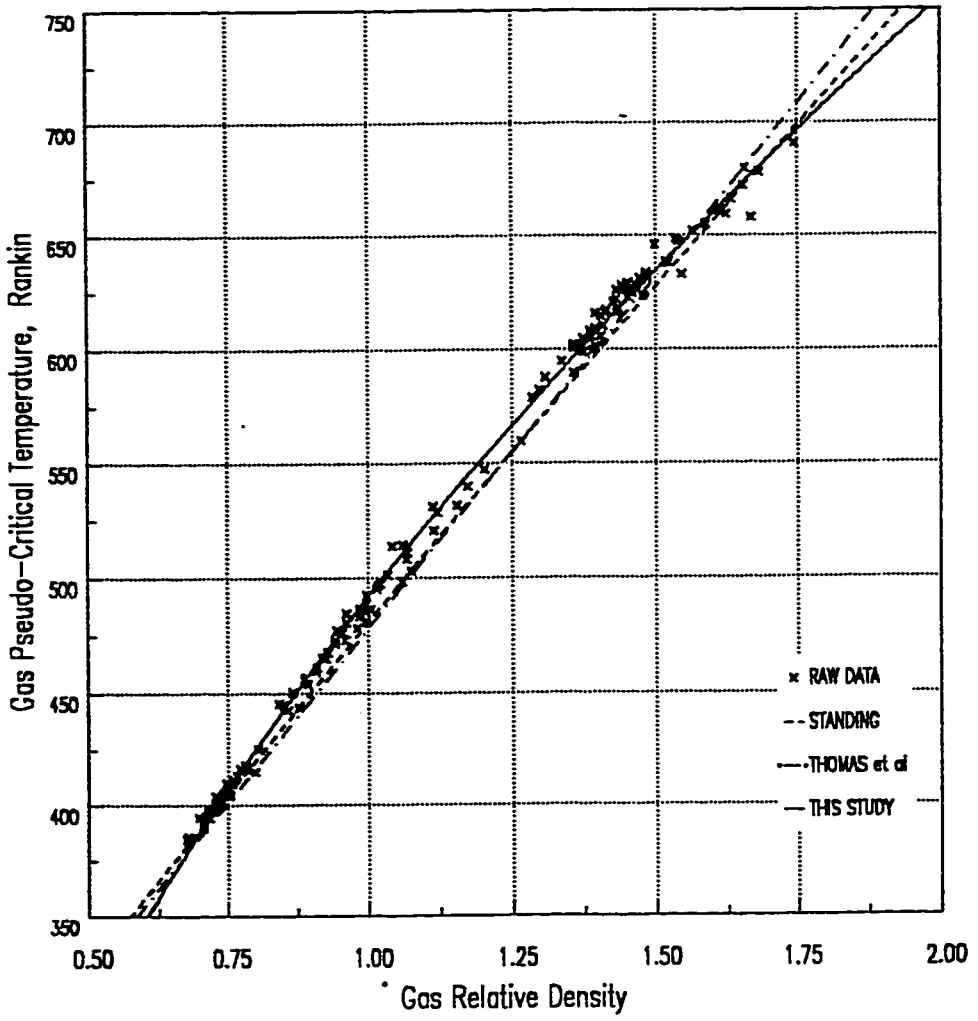


Fig. 18 - Comparison Plot For Gas Pseudo-Critical Temperature

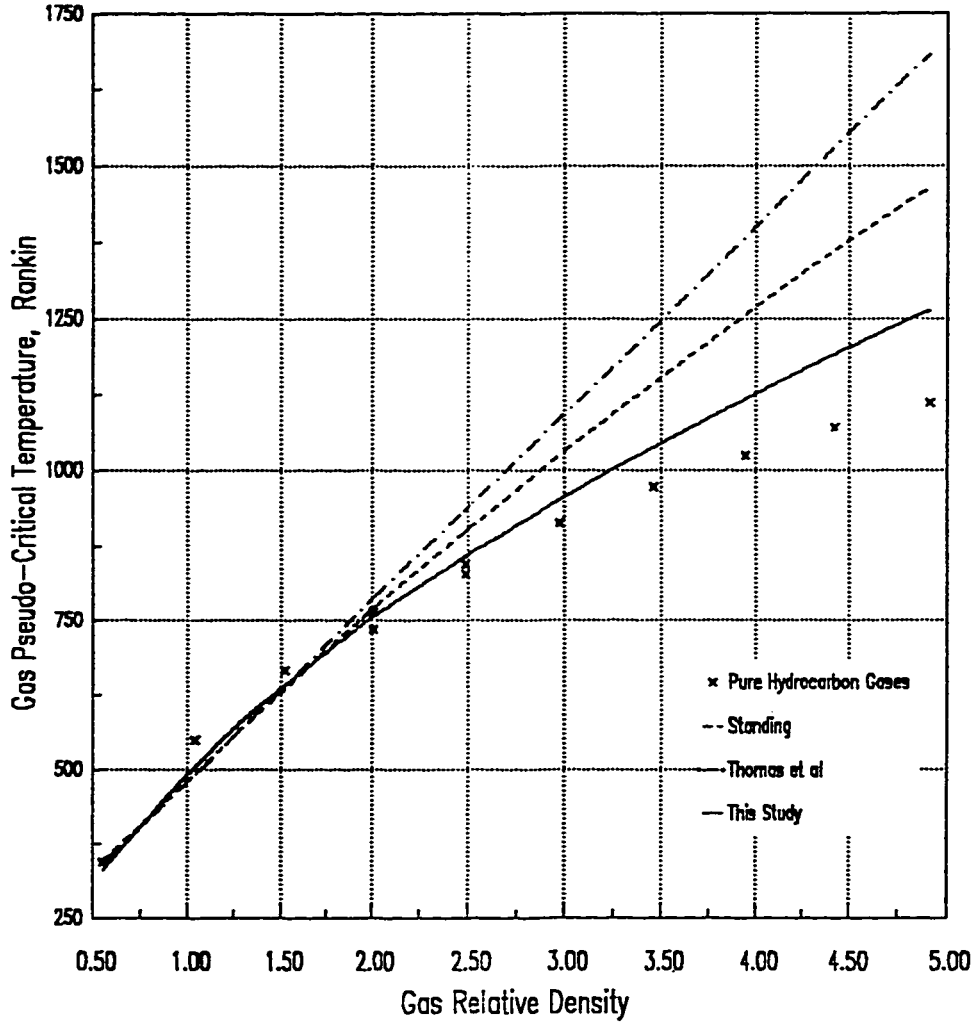


Fig. 19 - Comparison Plot For Gas Pseudo-Critical Temperature with Pure Hydrocarbon Gases

Table 10: STATISTICAL ACCURACY FOR GAS PSEUDO-CRITICAL PRESSURE DATA GROUPED BY GAS RELATIVE DENSITY

Gas Relative Density	<0.75	0.75-1.00	1.00-1.25	1.25-1.50	>1.50
Number of Data Points	28	41	17	42	17
AVERAGE ABSOLUTE PERCENT RELATIVE ERROR					
Standing	0.35	0.61	0.77	1.20	0.99
Thomas et al.	0.45	0.97	1.11	0.76	1.19
This Study	0.32	0.43	0.60	0.52	0.76
STANDARD DEVIATION					
Standing	0.37	0.60	0.71	0.69	0.79
Thomas et al.	0.36	0.66	0.71	0.69	1.18
This Study	0.39	0.55	0.71	0.69	0.84

Table 11: STATISTICAL ACCURACY FOR GAS PSEUDO-CRITICAL TEMPERATURE DATA GROUPED BY GAS RELATIVE DENSITY

Gas Relative Density	<0.75	0.75-1.00	1.00-1.25	1.25-1.50	>1.50
Number of Points	28	41	17	42	17
AVERAGE ABSOLUTE PERCENT RELATIVE ERROR					
Standing	0.58	1.41	1.75	1.83	0.81
Thomas et al.	1.49	2.06	2.12	1.44	0.99
This Study	0.57	0.62	0.99	0.74	0.62
STANDARD DEVIATION					
Standing	0.42	0.92	1.07	0.76	1.05
Thomas et al.	0.42	0.86	1.10	0.78	1.18
This Study	0.53	0.76	1.09	0.80	0.91

Figs. 20 and 21.

The correlations of this study are the best and most accurate correlations in all ranges of gas relative density. The accuracy of Standing's and Thomas et al.'s correlations vary from one range to another but, in general, Standing's correlations are better than Thomas et al.'s correlations. Therefore, the correlations can be placed in the following order with respect to their accuracy: this study, Standing and then Thomas et al.

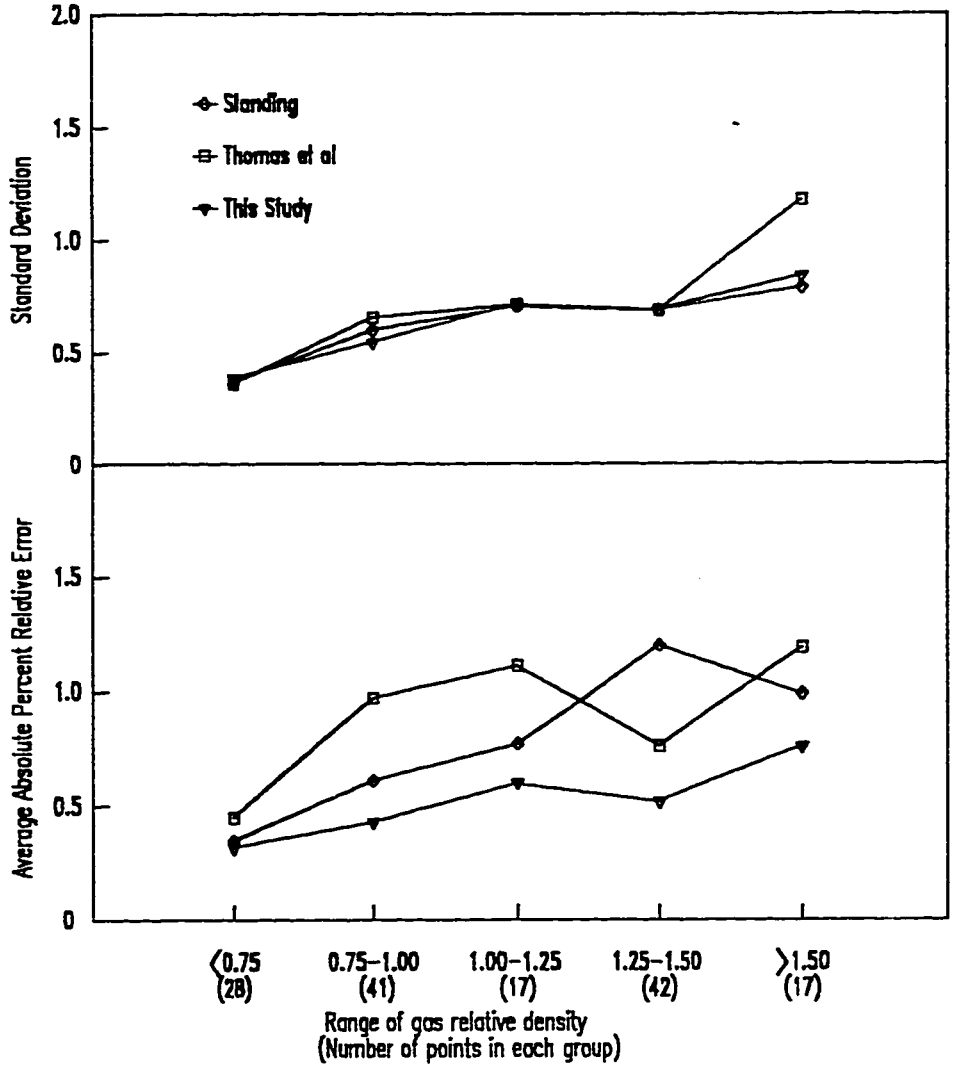


Fig. 20- Statistical Accuracy For Gas Pseudo-Critical Pressure Grouped by Gas Relative Density

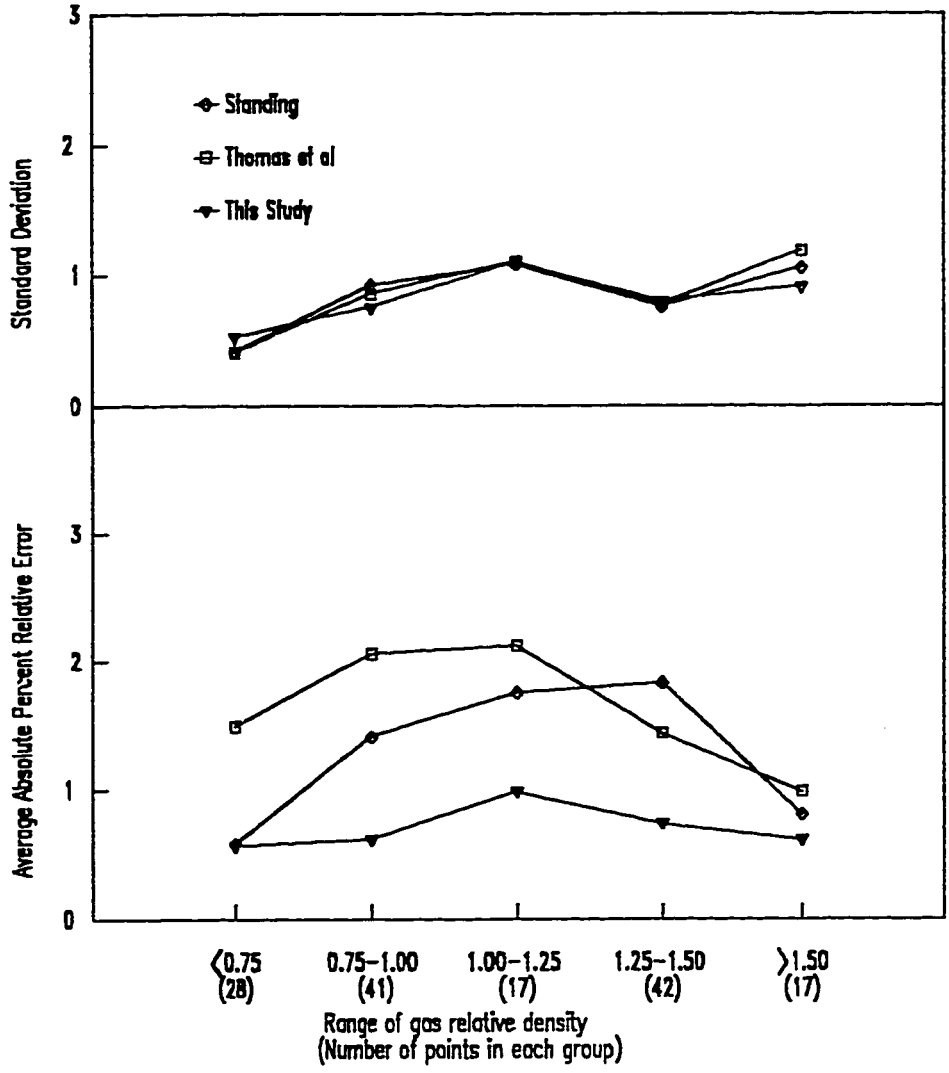


Fig. 21- Statistical Accuracy For Gas Pseudo-Critical Temperature Grouped by Gas Relative Density

6.2 Oil Isothermal Compressibility At and Below Bubblepoint Pressure

6.2.1 Statistical Analysis

For oil isothermal compressibility at and below bubblepoint, this study shows the best results (Table 12). The average absolute percent relative error for this study is 3.49. The maximum absolute percent relative error is 9.88. McCain et al.'s correlation, however, showed an average absolute percent relative error of 13.10 with a maximum absolute percent relative error of 117.67. This study also shows correlation coefficient of 0.9987 for this work.

6.2.2 Crossplots

The crossplot of oil isothermal compressibility at and below bubblepoint pressure correlation obtained by this study falls almost on the perfect 45° line implying excellent correlation.

For McCain et al. correlation, most of the data points fall above the perfect correlation line except for high values of oil compressibility; they fall below the perfect line. These crossplots are shown in Figs. 22 through 33 and presented in different ranges and format of oil compressibility values.

Table 12: STATISTICAL ACCURACY FOR OIL ISOTHERMAL COMPRESSIBILITY AT AND BELOW BUBBLEPOINT PRESSURE

Correlation	Er	Ea	Emin	Emax	r	s
McCain et al. 1988	-9.72	13.10	0.02	117.67	0.9516	17.5171
This Study 1990	-0.05	3.49	0.00	9.88	0.9987	4.1116

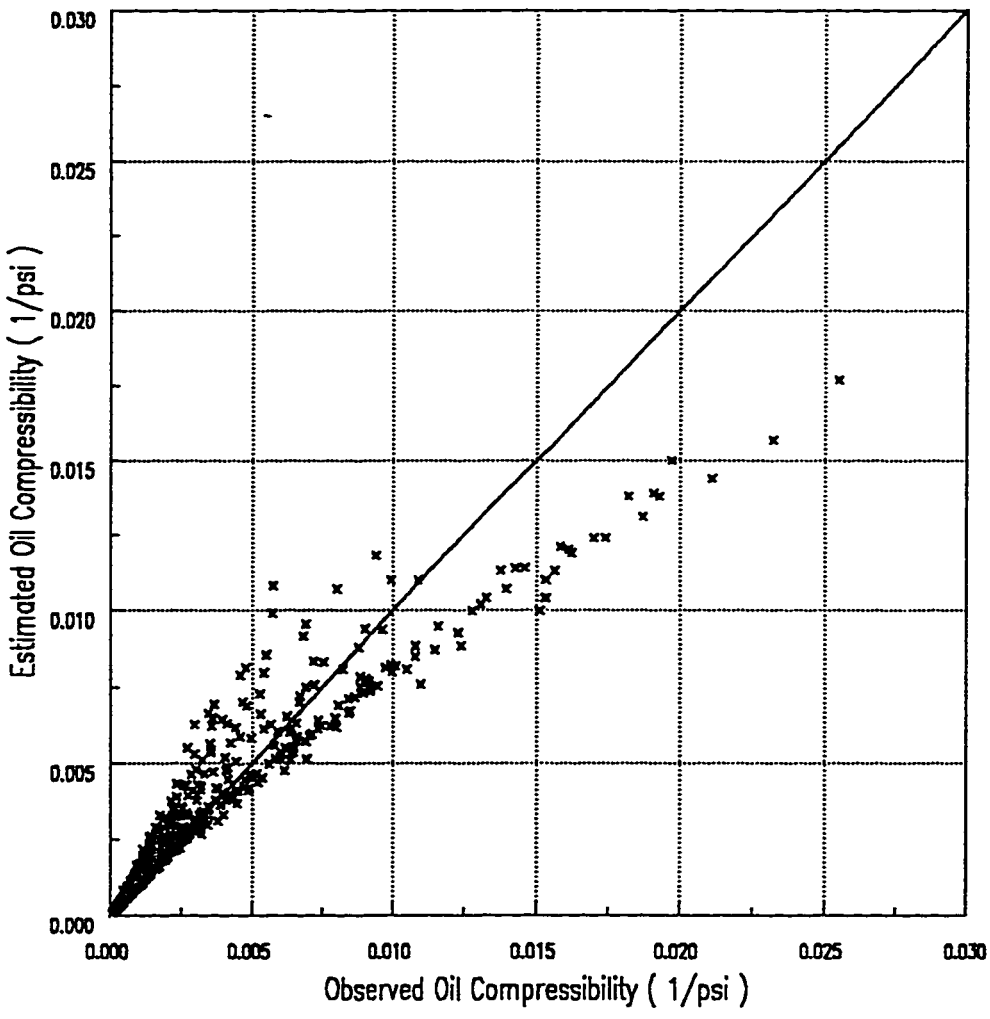


Fig. 22- Crossplot For Oil Compressibility at and below Bubblepoint Pressure (McCain et al)

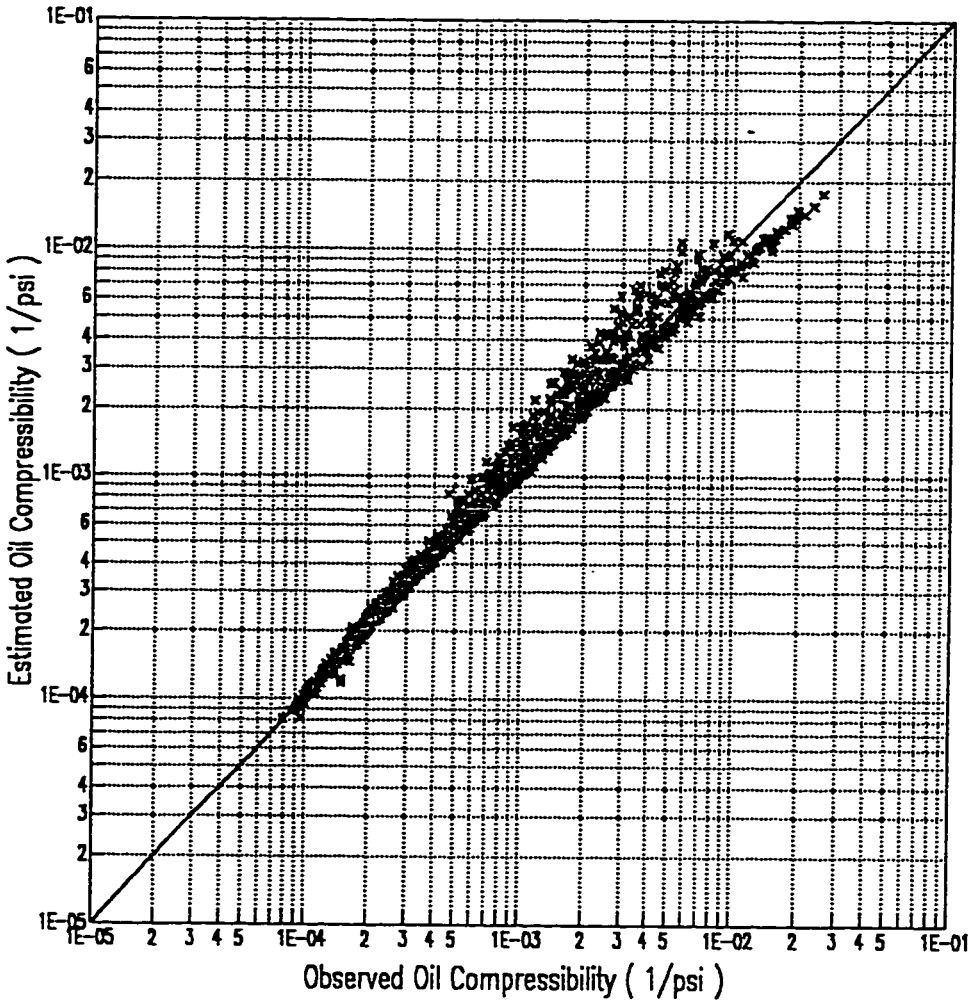


Fig. 23- Crossplot For Oil Compressibility at and below Bubblepoint Pressure (McCain et al., Log-Log)

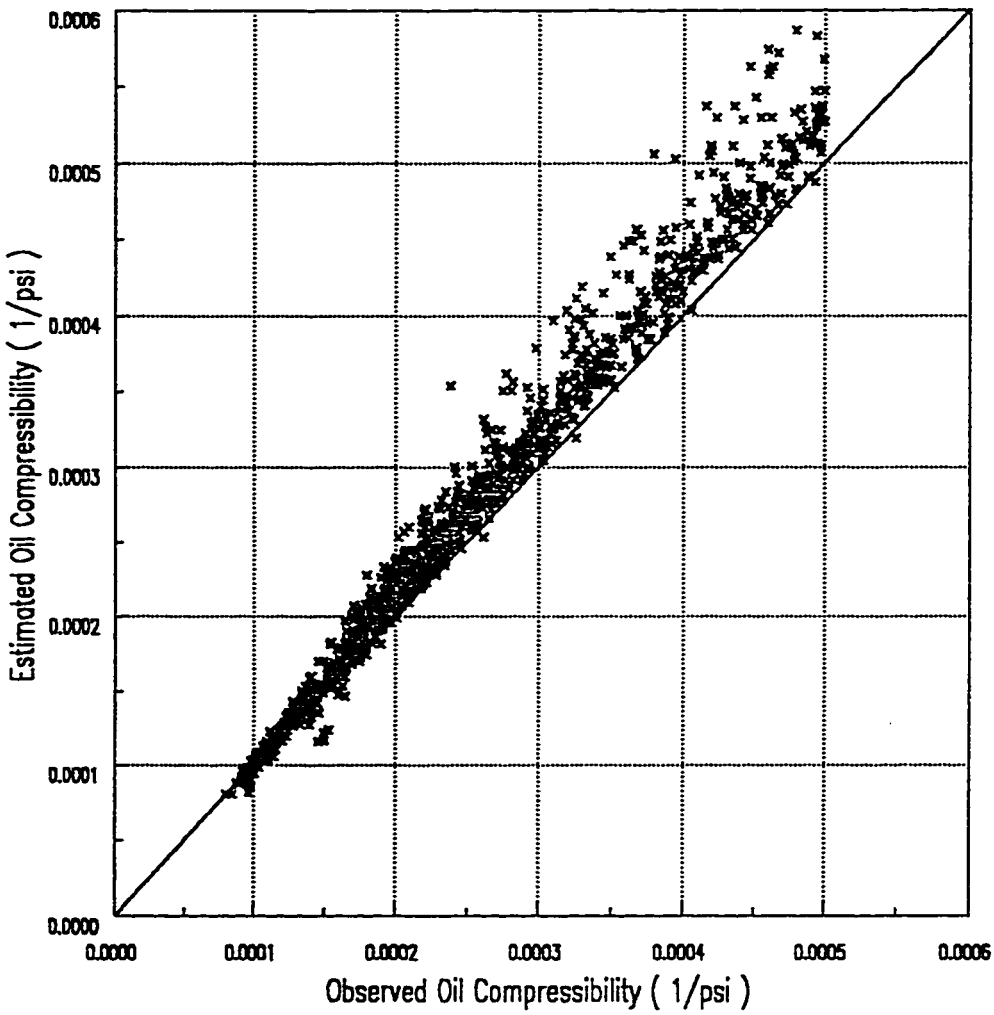


Fig. 24- Crossplot For Oil Compressibility at and below Bubblepoint Pressure (McCain et al, 0.0 - 0.0005 (1/psi))

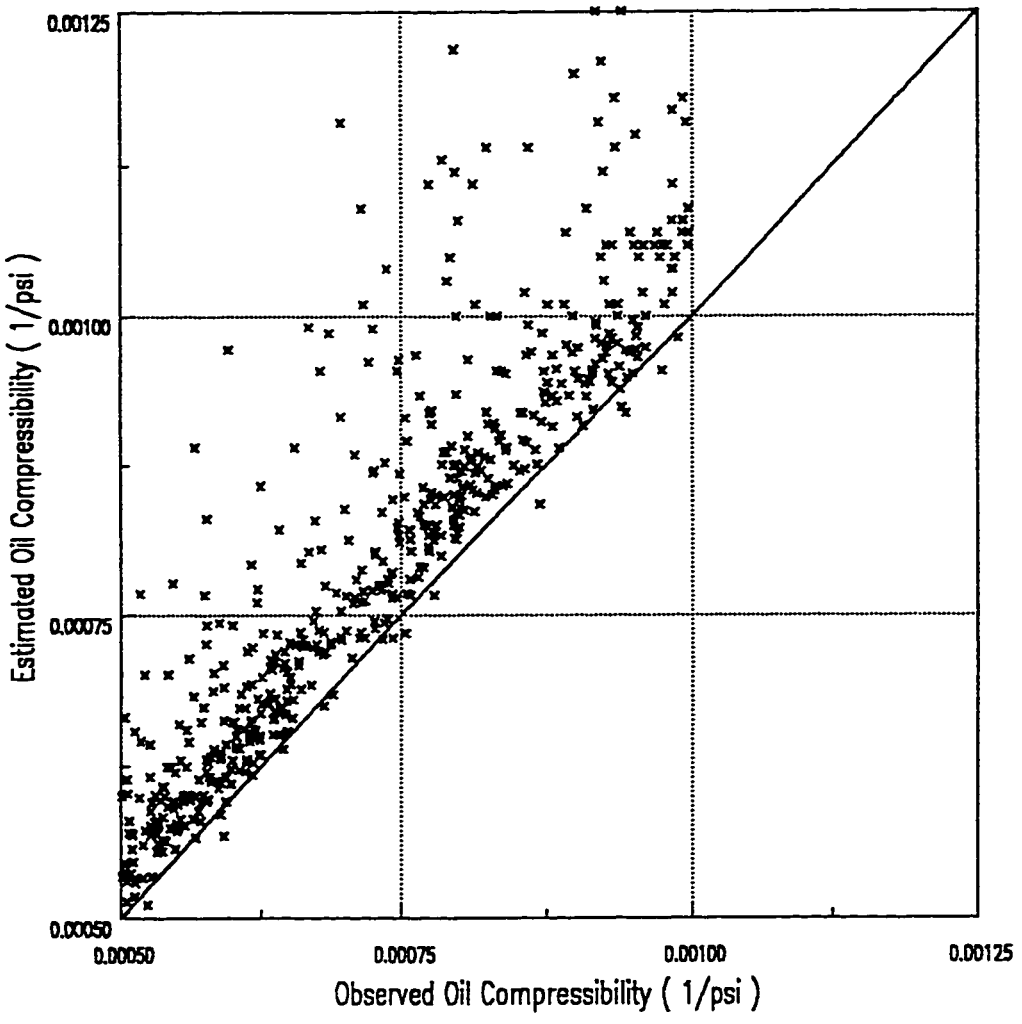


Fig. 25- Crossplot For Oil Compressibility at and below Bubblepoint Pressure (McCain et al, 0.0005 - 0.001 (1/psi))

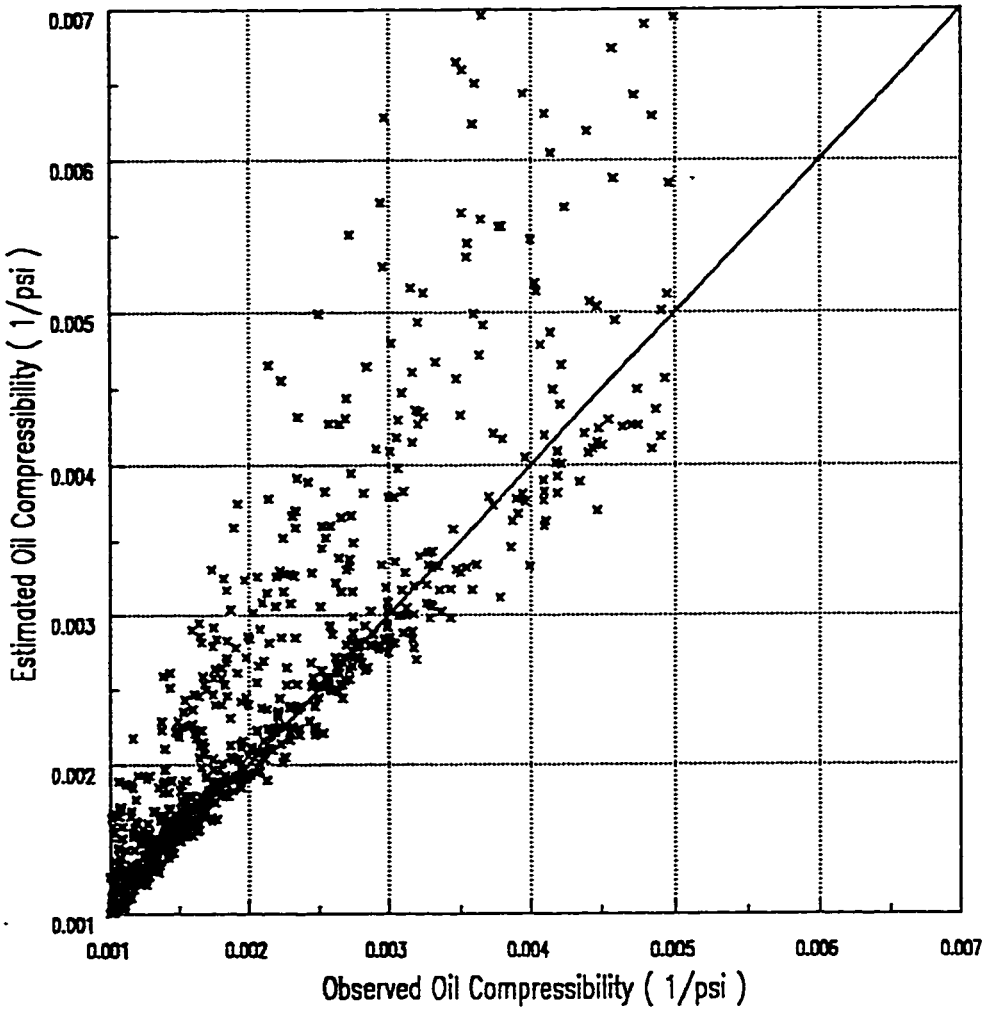


Fig. 26 - Crossplot For Oil Compressibility at and below Bubblepoint Pressure (McCain et al, 0.001 - 0.005 (1/psi))

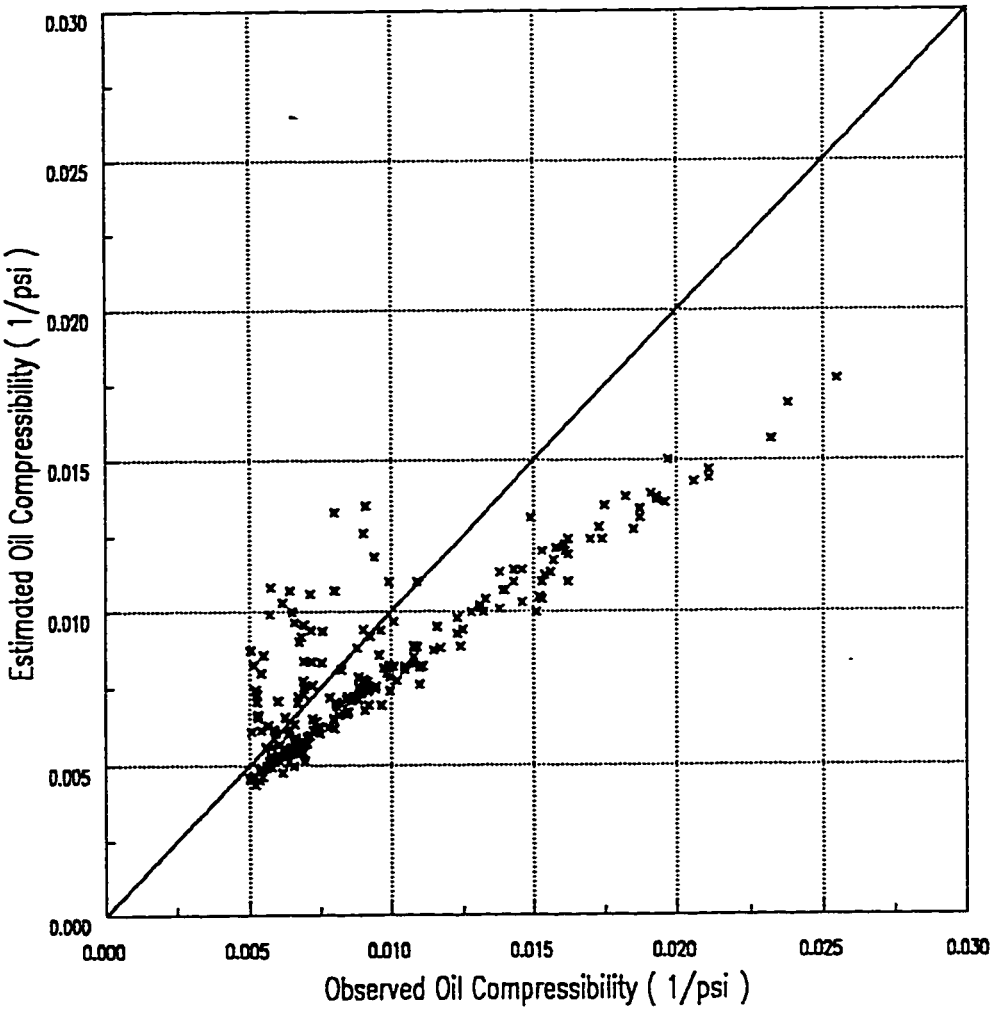


Fig. 27- Crossplot For Oil Compressibility at and below Bubblepoint Pressure (McCain et al, 0.005 - 0.0255 (1/psi))

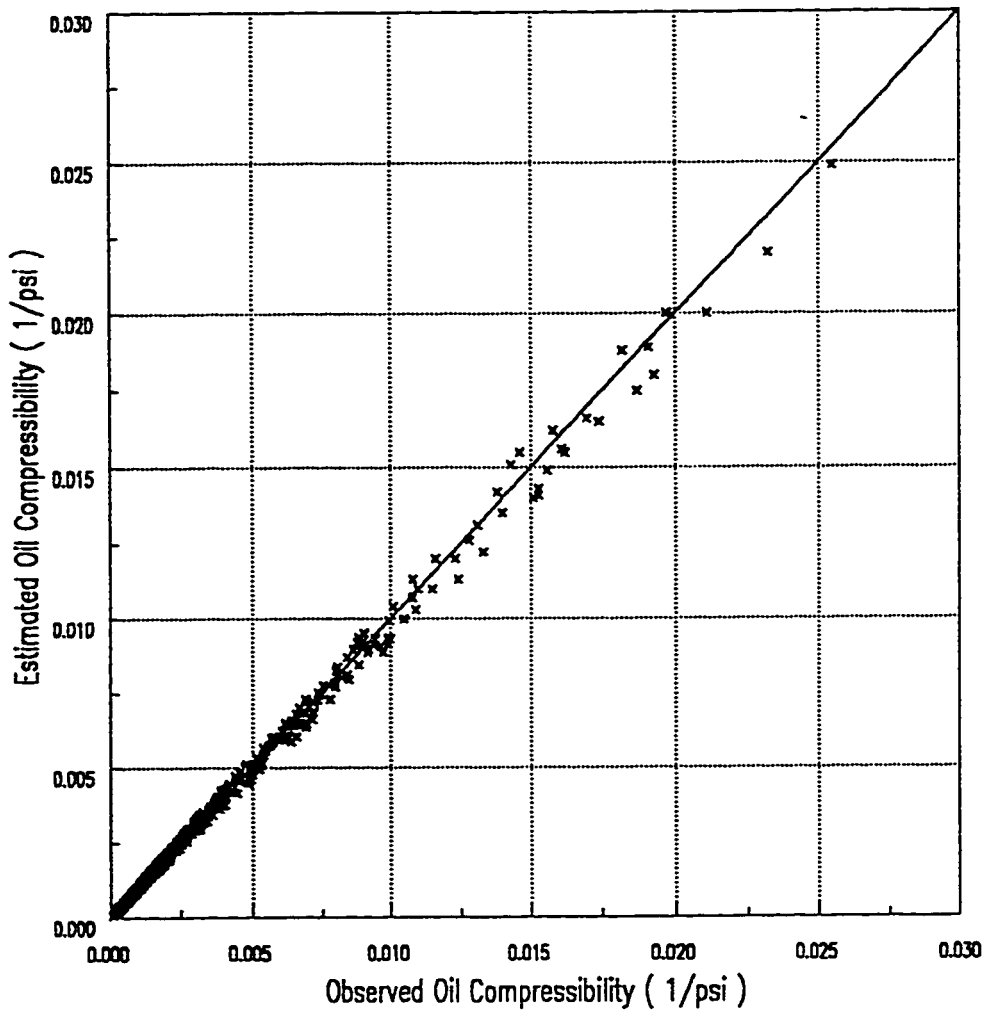


Fig. 28- Crossplot For Oil Compressibility at and below Bubblepoint Pressure (This Study)

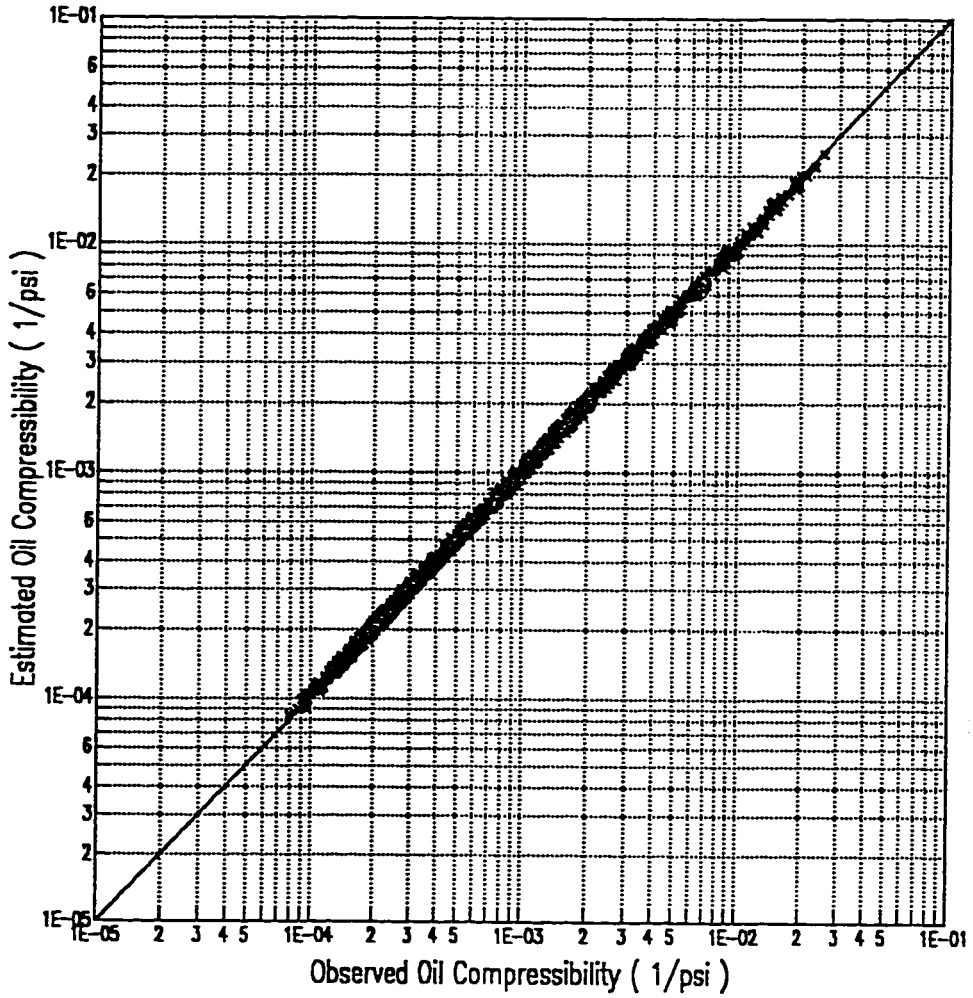


Fig. 29 - Crossplot For Oil Compressibility at and below Bubblepoint Pressure (This Study , Log-Log)

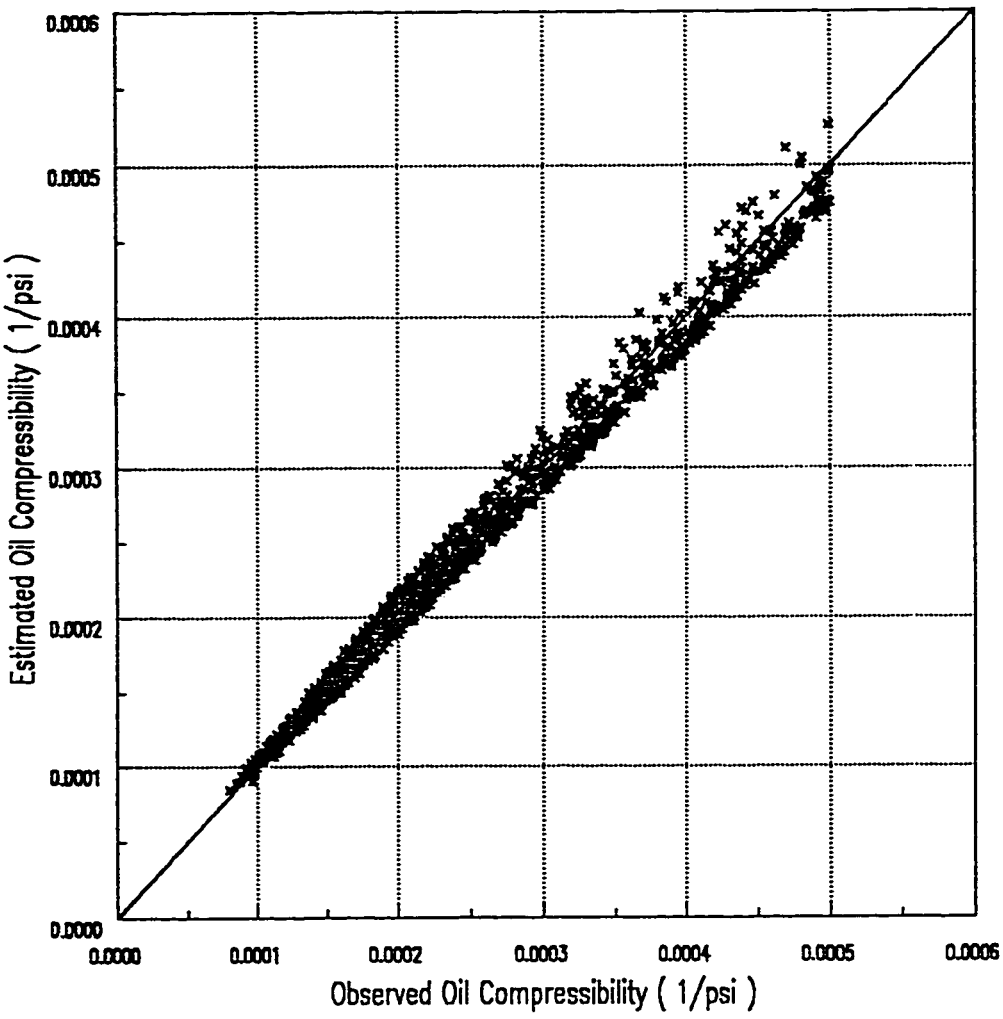


Fig. 30- Crossplot For Oil Compressibility at and below Bubblepoint Pressure (This Study, 0.0 - 0.0005 (1/psi))

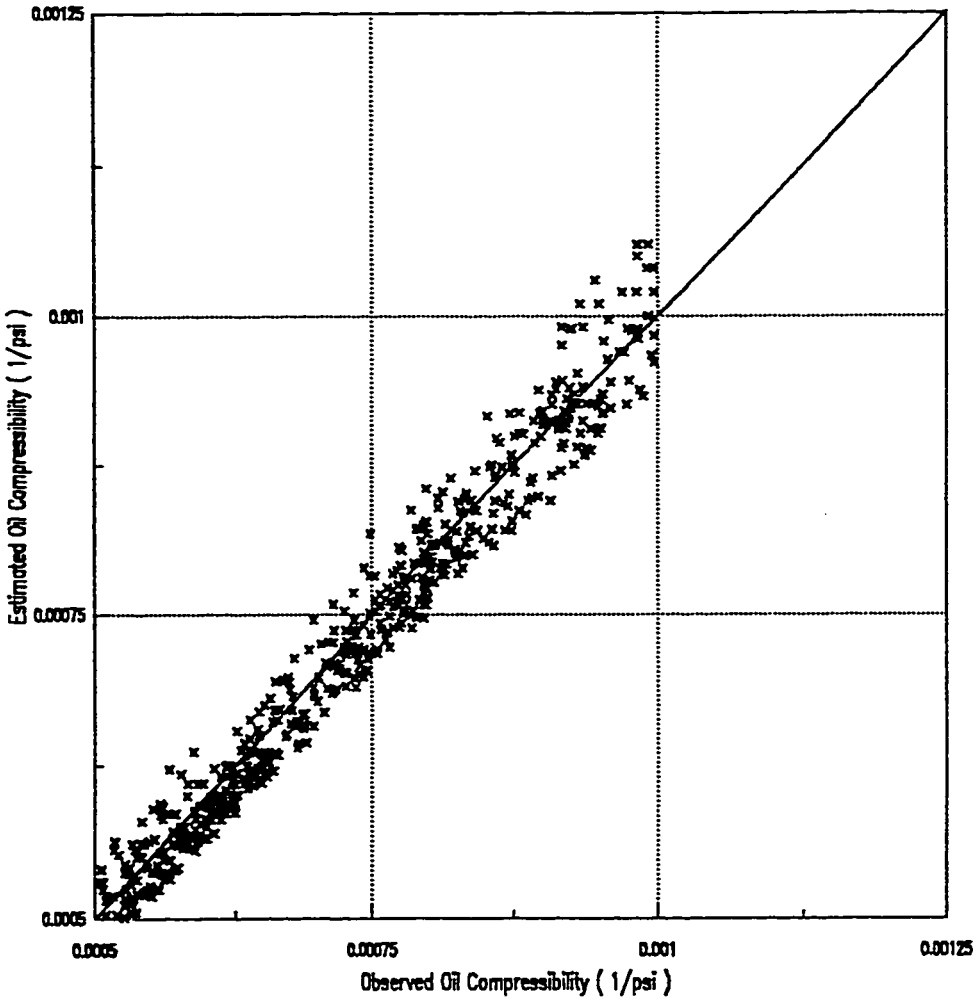


Fig. 31- Crossplot For Oil Compressibility at and below Bubblepoint Pressure (This Study, 0.0005 - 0.001 (1/psi))

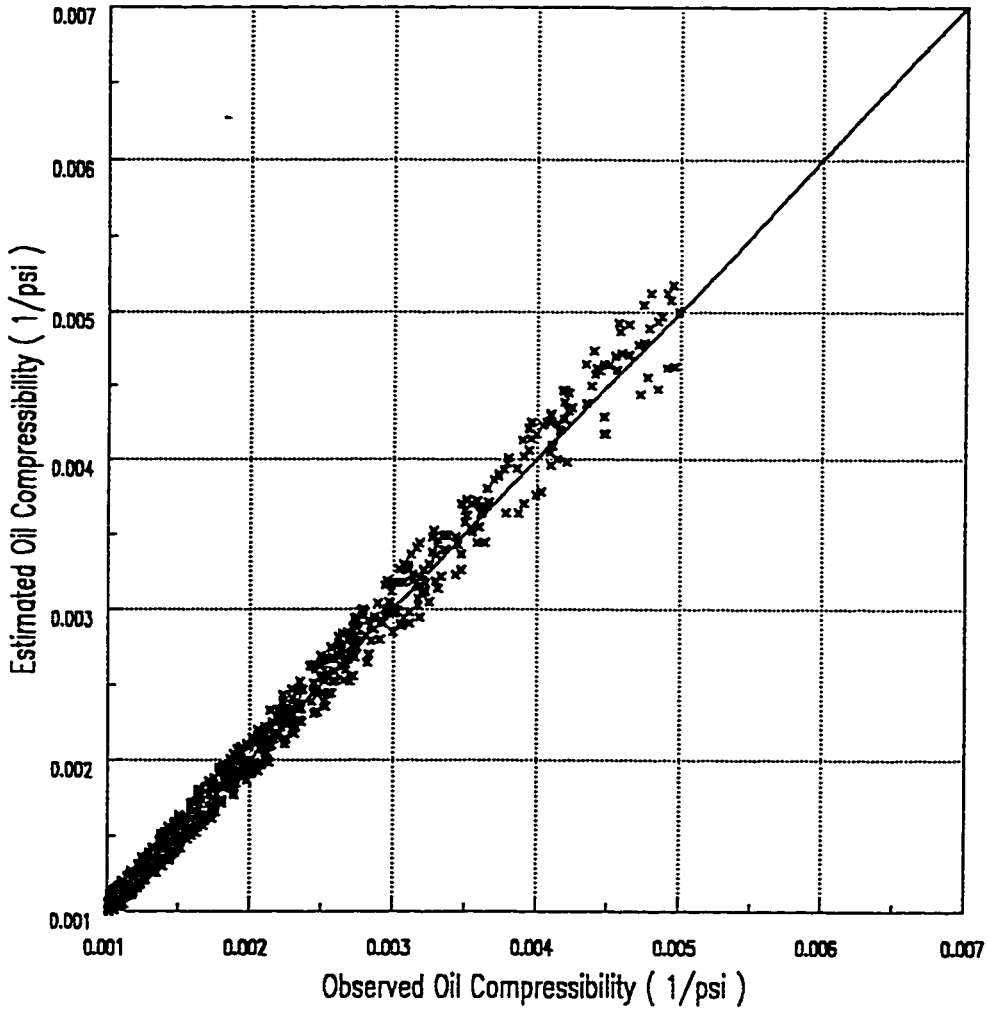


Fig. 32- Crossplot For Oil Compressibility at and below Bubblepoint Pressure (This study, 0.001 - 0.005 (1/psi))

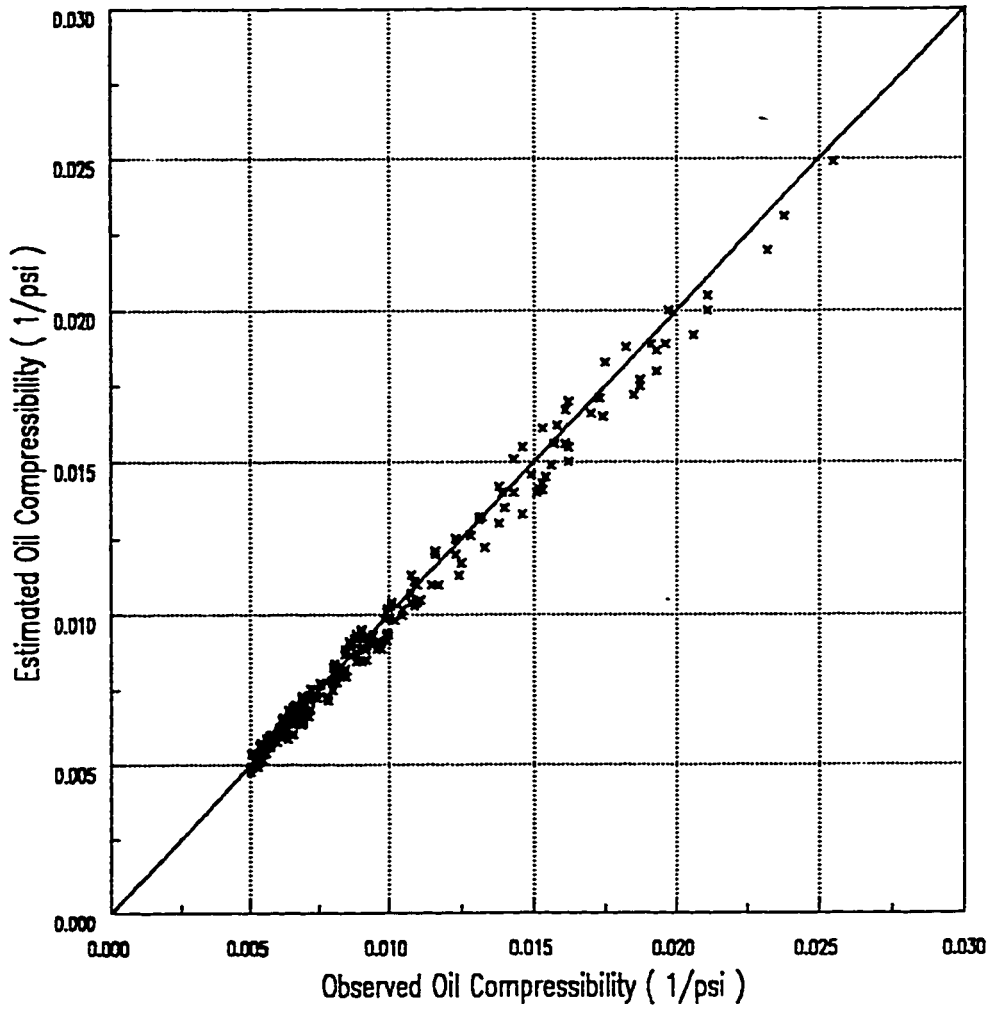


Fig. 33 - Crossplot For Oil Compressibility at and below Bubblepoint Pressure (This Study, 0.005 - .0255 (1/psi))

6.2.3 Incremental Analysis

This study and McCain et al. correlations were evaluated within specific ranges of pressure, since it is the most important parameter that contribute to this compressibility. The statistical results are shown in Table 13 and Fig. 34.

This type of analysis reveals that this study is the best and most accurate correlation for all ranges of pressure.

This analysis also shows that McCain et al. correlation is giving very high average absolute percent relative error beyond its limit of 4.5 reported in literature for all selected ranges of pressure except 2500-3000 psia pressure range. Moreover, McCain et al. correlation gives very high average absolute percent relative error (>20%) for pressure values lower that 500 psia or greater than 3500 psia.

Table 13: STATISTICAL ACCURACY FOR OIL ISOTHERMAL COMPRESSIBILITY AT AND BELOW BUBBLEPOINT PRESSURE DATA GROUPED BY PRESSURE

Pressure Range	<500	500-1000	1000-1500	1500-2000	2000-2500	2500-3000	3000-3500	>3500
Number of Points	863	751	394	391	162	53	16	5
AVERAGE ABSOLUTE PERCENT RELATIVE ERROR								
McCain et al.	22.37	9.41	9.61	8.10	5.03	3.77	4.85	20.36
This Study	3.73	3.18	3.54	3.44	3.39	3.66	4.51	4.92
STANDARD DEVIATION								
McCain et al.	28.33	9.02	5.92	5.11	4.23	4.62	4.90	1.52
This Study	4.33	3.66	3.83	4.08	3.70	3.85	4.23	1.03

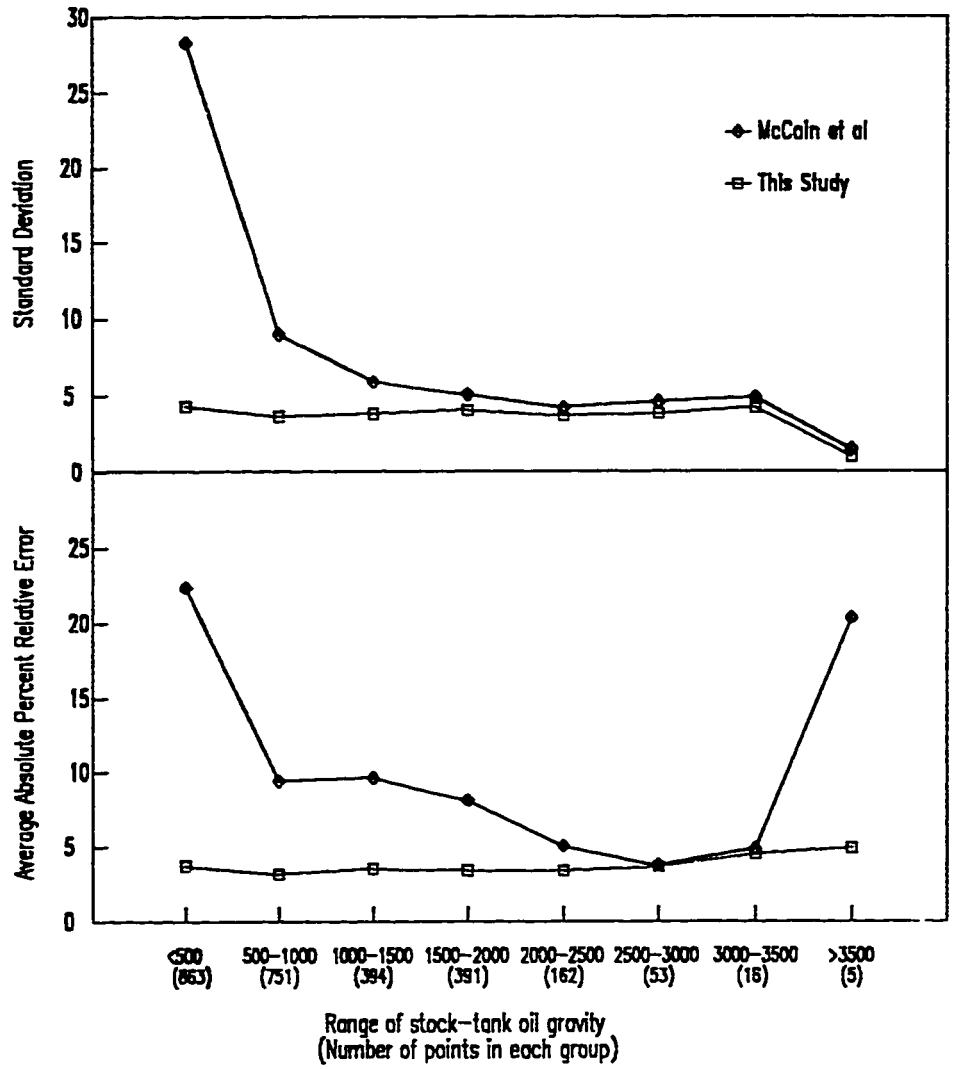


Fig. 34- Statistical Accuracy For Oil Compressibility at and below Bubblepoint Pressure Grouped by Pressure

CHAPTER 7

Chapter 7

CONCLUSIONS

1. Oil isothermal compressibility correlation to compute the compressibility values at and below the bubblepoint pressure, was developed.

2. Average percent relative errors, average absolute percent relative error, and standard deviation from observed data are lower for this study than for estimation based on McCain et al. correlation.

3. Correlations to calculate gas pseudo-critical pressure and temperature for hydrocarbon gas mixtures, were also developed.

4. These correlations are more accurate than Standing and Thomas et al. as indicated by average absolute percent relative errors and standard deviations.

5. The existing and the newly developed correlations were evaluated against selected ranges of pressure for oil compressibility and ranges of gas relative density for the gas pseudo-critical properties. The results showed that the newly developed correlations in this study are the best for all ranges.

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